



Integrating industrial engineering and environmental sustainability for a sustainable competitive advantage in South Africa

M Roopa

 **orcid.org/ 0000-0002-3852-2192**

Dissertation accepted in fulfilment of the requirements for the
degree *Doctor of Philosophy in Engineering with Industrial
Engineering* at the North-West University

Promoter: Prof R Siriram

Graduation: September 2026

“The greatest threat to our planet is the belief that someone else will save it”

- Robert Swan

Abstract

Environmental sustainability (ES) remains increasingly relevant to our world and more challenging for developing countries to achieve. At the same time, companies try to remain competitive and often turn to sustainable solutions for a competitive advantage. Concurrently, the field of Industrial Engineering (IE) has received growing interest in all parts of the world, in various sectors, since its inception during the first industrial revolution. The specialised discipline of IE has knowledge that yields productivity gains; yet no taxonomy model gives clear recognition or associations with environmental sustainability. The knowledge pools of IE and ES currently lack a formalised, visible classification. This disparate leaves developing countries unable to successfully adopt environmental sustainability in order to ensure a sustainable competitive advantage. South Africa is no exception to this.

This study strives to investigate IE knowledge to identify ways in which to enhance environmental sustainability in South Africa, using a sustainable competitive advantage. The core focus identifies various strategies, theories, and methods and practices (knowledge components) that are later linked with the strategic, tactical and operational business execution levels. It also investigates transdisciplinary knowledge creation, arguing that IE is capable of producing such knowledge. A staged Design Science Research (DSR) paradigm is followed and contextualised by the research onion using four distinct phases. The research design begins with a Systematic Literature Review and thematic analysis to explore IE knowledge and environmental sustainability as part of the rigour cycle of DSR. In the second phase, the relevance cycle involves interviewing South African industrial engineers and environmental sustainability managers to identify knowledge components for a sustainable competitive advantage, which are applied in industry and academia. The last two phases entail the design and validation of a Pyramid Water Fountain model that ensures a sustainable competitive advantage.

The Abstract, Contextualise and Design (ACD) methodology is coined as a transdisciplinary design methodology used to create the artefact. The validation entailed a confirmatory focus group. These findings can thus be generalised to other developing countries by drawing on knowledge from the IE and environmental sustainability domains within transdisciplinary knowledge contexts. This research demonstrates transdisciplinarity and systemic environmental problem-solving, as well as sustainable competitive advantages that are inspired by the notions of integrating knowledge from IE and ES.

Keywords: industrial engineering, environmental sustainability, sustainable competitive advantage, transdisciplinary knowledge, South Africa.

Preface

Format of thesis

The format of this thesis is in accordance with the academic rules of the North-West University (approved September 21st, 2017, with revisions on June 20th, 2019), where:

Rule **A.5.10.5** states: “Where a candidate is allowed to submit the research product in the form of research articles, such research product must be presented for examination purposes as an integrated unit, supplemented with a problem statement, an introduction and a synoptic conclusion as prescribed by faculty rules and the manuscript submission guidelines, or the URL link to the manuscript guidelines of the journal or journals concerned.”

Rule **A.5.10.8** states: “Where any research article, manuscript or internationally examined patent to which the candidate for a doctoral degree and other authors or inventors have contributed is submitted as the research product of a doctoral degree programme, the candidate must obtain a written statement from each co-author and co-inventor in which it is stated that such co-author or co-inventor grants permission for the research product to be used for the stated purpose, and in which it is further indicated what each co-author's or co-inventor's share in the research product concerned was.”

Rule **A.5.10.9** states: “Where co-authors or co-inventors as contemplated in rule 5.10.8 were involved in the development of the research product, the candidate must mention this fact in the preface, and must include the statement of each co-author or co-inventor in the thesis, mini-thesis or research report immediately following the preface to the research product.”

The following paper has been published in the Journal of Sustainability:

M. Roopa, R. Siriram and R. Coetzee, “Exploring Industrial Engineering Knowledge and Environmental Sustainability”.

Doi: <https://doi.org/10.3390/su16177392>

The following conference paper has been published in the conference proceedings of SAIIE 34: Illuminate:

M. Roopa, "An Industrial Engineering lighthouse model for transdisciplinary problem solving and sustainable development in South Africa."

Doi: <https://doi.org/10.52202/078172-0014>

The following paper has been published in the Journal of Sustainable Futures:

M. Roopa and R. Siriram “Identifying Harmony between Industrial Engineering and Environmental Sustainability in South Africa”.

Doi: <https://doi.org/10.1016/j.sfr.2026.101695>.

Based on the review by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 27 March 2024, the NWU-ENG-REC hereby cleared this study as a low-risk study, assigning it the ethics number NWU-00235-23-A3.

Format of numbering and referencing

It is important to note that the formatting, referencing style and numbering of tables and figures abide by those dictated by the manuscripts and have been adapted for consistency in this thesis. The format of each manuscript is also structured according to the journal guidelines. For this reason, certain published works have become standalone chapters as part of the research. The reference list also appears in those chapters that contain the journal paper findings. Furthermore, the header, footer, page numbers and formatting appear differently in Chapter 4 and Chapter 5. The headings and original content of the publications cannot be modified.

STATEMENT OF CO-AUTHORS

To whom it may concern,

The listed co-authors hereby give consent that Meelan Roopa may submit the publication “Exploring Industrial Engineering Knowledge and environmental Sustainability” as part of his thesis titled, “Integrating industrial engineering and environmental sustainability knowledge for a sustainable competitive advantage in South Africa” for the degree Doctor of Philosophy in IE, at the North-West University (NWU). This letter of consent complies with rules A4.10.8 and A4.10.9 of the academic rules, as stipulated by the North-West University.

_____	<u>4 March 2026</u>	<u>Sandton</u>
Prof Rajenlall Siriram	Date	Signed at

_____	<u>6 March 2026</u>	<u>Potchefstroom</u>
Prof Rojanette Coetzee	Date	Signed at

STATEMENT OF CO-AUTHORS

To whom it may concern,

The listed co-authors hereby give consent that Meelan Roopa may submit the publications “Identifying harmony between industrial engineering and environmental sustainability in South Africa” and “A multi-use case analysis for a sustainable competitive advantage using industrial engineering and environmental sustainability knowledge” as part of his thesis titled, “Integrating industrial engineering and environmental sustainability knowledge for a sustainable competitive advantage in South Africa” for the degree Doctor of Philosophy in IE, at the North-West University (NWU). This letter of consent complies with rules A4.10.8 and A4.10.9 of the academic rules, as stipulated by the North-West University.

_____	4 May 2026	Sandton
Prof Rajenlall Siriram	Date	Signed at

Acknowledgements

I would like to give recognition to the following individuals who have made a sustained impact on my PhD journey:

- To my inspiring daughter **Myla**, thank you for joining me along this path and for helping Dad “Tell his engineering story”. I can’t imagine this becoming a storybook per se, but perhaps a coffee table book for you. I will always keep making you proud.
- To my late dad **Prakash** and my mom **Sherini**: thank you for nurturing my curiosity, creativity and appreciation for knowledge. I am grateful for who you have made me today.
- My little older sister **Sanam**, thank you for seeing and manifesting the “Professor” energy all these years. It is something I still aspire to achieve in the near future.
- To **Prof Raj**, I truly believe much of the momentum would not have been possible without your guidance. Thank you for your time, quality feedback and encouragement throughout this journey.
- To my **friends** Mia, Anouska and Johnson, thank you for rooting for me during all these years.
- To all interview and confirmatory focus group **participants**, whose insight and subject matter advice have helped in conceptually defining my work.
- My old and new **colleagues** during this academic venture: thanks for your coffee chats, support, advice and “How is the PhD?” check-ins, which were always valued.
- To my **examiners**, thank you for evaluating my thesis and for sharing your expertise and constructive feedback on my research.

TABLE OF CONTENTS

1	INTRODUCTION	16
1.1	Background	16
1.2	Research focus	18
1.3	Research gap	23
1.4	Research opportunity	25
1.5	Problem statement	25
1.6	Research aim, questions and objectives	25
1.6.1	Research aim.....	25
1.6.2	Research questions	25
1.6.3	Research objectives	26
1.7	Research design.....	26
1.8	Novelty and contribution	26
1.9	Chapter outline.....	27
1.10	Chapter summary	27
2	LITERATURE REVIEW	29
2.1	Introduction.....	29
2.2.1	Origins.....	30
2.2.2	Taxonomies	31
2.2.3	Environmental sustainability association.....	32
2.3.1	Industrialisation	34
2.3.2	Environmental performance	35
2.3.3	Sustainable Development Goals (SDGs).....	36
2.3.4	Circular Economy	36
2.3.5	Green innovation	37
2.4	Forms of knowledge.....	38
2.4.1	Transdisciplinary knowledge	38
2.4.2	Tacit and Explicit knowledge.....	44
2.4.3	Knowledge life cycle and spiral model.....	45
2.4.4	Knowledge supply chain	46
2.4.5	Theory, principles and practice.....	47
2.5	Sustainable competitive advantage.....	48
2.5.1	Resource-Based View (RBV).....	50
2.5.2	VRIO framework.....	51
2.5.3	Dynamic capabilities	52
2.5.4	Natural-Resource-Based View (NRBV).....	53
2.5.5	Debate between NBRV and Dynamic Capabilities.....	54
2.6	Biomimicry	55
2.7	Chapter summary	57

3	RESEARCH DESIGN	59
3.1	Introduction	59
3.2	Research onion layers	60
3.2.1	Philosophies	60
3.2.2	Approaches	61
3.2.3	Strategies	61
3.2.4	Choices	61
3.2.5	Time horizons	62
3.2.6	Techniques and procedures	62
3.3	Contextualised research onion	62
3.4	Selection between DSR and ADR	65
3.5	Stage 1 (Rigour cycle)	69
3.6	Stage 2 (Relevance Cycle)	71
3.7	Stage 3 (Design cycle build artefact)	76
3.8	Stage 4 (Design cycle evaluate artefact)	77
3.8.1	Use Case Analysis	77
3.8.2	Confirmatory Focus Group	79
3.8.3	Verification and validation of TD artefact	84
3.9	Limitations	84
3.10	Ethical considerations	85
3.11	Chapter summary	85
4	EXPLORING INDUSTRIAL ENGINEERING KNOWLEDGE AND ENVIRONMENTAL SUSTAINABILITY	86
5	IDENTIFYING HARMONY BETWEEN INDUSTRIAL ENGINEERING AND ENVIRONMENTAL SUSTAINABILITY IN SOUTH AFRICA	91
6	AN INDUSTRIAL ENGINEERING LIGHTHOUSE MODEL FOR TRANSDISCIPLINARY PROBLEM SOLVING AND SUSTAINABLE DEVELOPMENT IN SOUTH AFRICA	95
7	A TRANSDISCIPLINARY PYRAMID WATERFALL FOUNTAIN MODEL FOR A SUSTAINABLE COMPETITIVE ADVANTAGE	99
8	ANALYSIS OF SLR AND INTERVIEWS	104
8.1	Introduction	104
8.2	SLR	104
8.3	Interviews	106
8.4	Chapter summary	110
9	USE CASE ANALYSIS (UCA)	111
10	CONFIRMATORY FOCUS GROUP	116
10.1	Introduction	116

10.2	Use Case Analysis (UCA) reflection.....	116
10.3	CFG method and event details.....	117
10.4	CFG data and analysis	117
10.4.1	Survey data	117
10.4.2	Discussion topic 1 findings	121
10.4.3	Discussion topic 2 findings	122
10.4.4	Discussion topic 3 findings	123
10.4.5	Discussion topic 4 findings	124
10.5	Synthesised analysis of results	126
10.6	Chapter summary	127
11	DISCUSSION.....	129
11.1	Introduction.....	129
11.2	SLR	129
11.2.1	The literature between IE and ES	129
11.2.2	Subconscious solution space.....	130
11.2.3	Transdisciplinarity as a bridging mechanism.....	130
11.3	Interviews.....	131
11.3.1	Transdisciplinary knowledge from industry and academia.....	131
11.3.2	Strategy, greenwashing and the embedded sustainability imperative	131
11.3.3	Knowledge components: strategies, theories, methods and practices ...	132
11.3.4	Waste monetisation and the value reframing of sustainability.....	133
11.4	Use Case Analysis	134
11.4.1	Sensing: identifying opportunities and threats	134
11.4.2	Seizing: mobilising resources to capture value	134
11.4.3	Transforming: reconfiguring systems and culture.....	134
11.5	The IE Pyramid Water Fountain Model.....	135
11.5.1	Design logic and theoretical alignment.....	135
11.5.2	NRBV, RBV and the competitive logic of the framework.....	136
11.5.3	Biomimicry and the nature-inspired design logic	136
11.6	Confirmatory Focus Group.....	137
11.7	Industrial Ecology and Industrial Engineering.....	138
11.8	Synthesis and implications.....	138
11.9	Chapter summary	139
12	CONCLUSIONS, NOVELTY, LIMITATIONS AND RECOMMENDATIONS	141
12.1	Concluding remarks	141
12.2	Novelty	142
12.3	Limitations and Recommendations	144
	REFERENCES.....	147

LIST OF TABLES

Table 1 Scimago rankings on research publications per region from 1996 to 2023	20
Table 2 Green wastes from Zokaei <i>et al.</i> (2017) with context.....	34
Table 3: Central parts of TD co-production processes reproduced from Polk (2015)....	41
Table 4: TD co-production challenges reproduced from Polk (2015)	42
Table 5 Research design summary	63
Table 6 SLR search protocol	70
Table 7 Summary of interview types with shortcomings informed by Alsaawi (2014)....	71
Table 8: Research protocol adapted from Creswell and Creswell (2017).....	73
Table 9 Saturation identifiers employed in this research	74
Table 10: Summary of advantages and disadvantages of focus groups adapted from Mazza and Berre (2007)	79
Table 11: Steps for organising a focus group in Design Science Research applied to the study	81
Table 12: Confirmatory Focus Group Agenda	82
Table 13 Knowledge components filtered out of PWTA and TD artefact creation.....	109
Table 14 CFG Survey results	117
Table 15 CFG Sentiment analysis and code density co-occurrence	119
Table 16: Integrated knowledge components used for PWTA.....	176
Table 17 Integrated knowledge component PWTA calculations	186

LIST OF FIGURES

Figure 1 Industrial and Systems Engineering Knowledge Areas adapted from (IISE) (2021b)	18
Figure 2 IE domain definitions from Salvendy (2001).....	19
Figure 3 Minimal System Representation of research focus [Researcher's own work].....	22
Figure 4: Research gap delineation.....	24
Figure 5 Literature Review Overview	29
Figure 6 Evolution of economy, society and environment adapted from Darwish (2018).....	33

Figure 7 Transdisciplinary, interdisciplinary, multidisciplinary and disciplinary overview redrawn from Tress <i>et al.</i> (2005) and reproduced with permission from Roopa <i>et al.</i> (2024).....	39
Figure 8 Transdisciplinary as outlined by Darian-Smith and McCarty (2016)	40
Figure 9 Differences in research types redrawn from Sakao and Brambila-Macias (2018), inspired by Cronin (2008).....	41
Figure 10 Integration degree and stakeholder involvement approach redrawn from Sakao and Brambila-Macias (2018).....	43
Figure 11 Knowledge Generation SECI model from Nonaka and Nishiguchi (2001).....	44
Figure 12 Interrelated knowledge life cycle redrawn from Nonaka and Takeuchi (1995).....	45
Figure 13 Knowledge work processes as knowledge spiral redrawn from Seufert <i>et al.</i> (2004).....	46
Figure 14 The Knowledge Supply Chain redrawn from Du Preez and Louw (2007).....	47
Figure 15 Difference between theory, principles and practice, redrawn from Schlüter <i>et al.</i> (2023) and similar to Koskela and Kagioglou (2005).....	48
Figure 16 Sustainability and Organisational Leaders vs. Laggards Framework redrawn from ISS Insights (2026).....	49
Figure 17 Sustainable Competitive Advantage Factors redrawn from Sołoduch-Pelc and Sulich (2020)	50
Figure 18: Research framework inspired by Darwish (2018)	59
Figure 19 Research onion redrawn from Saunders <i>et al.</i> (2009).....	60
Figure 20 Contextualised Research onion	62
Figure 21 Design Science Research Cycles redrawn from Hevner <i>et al.</i> (2010).....	67
Figure 22 DSR applied in this research adapted from Hevner (2007).....	67
Figure 23 Research design with DSR staged with chapter outline and techniques	68
Figure 24 Title word cloud of 24 papers from SLR.....	104
Figure 25 Cumulative years of SLR search results.....	105
Figure 28 Geographical charting of SLR data.....	106
Figure 29 Industry representation of interview sample.....	107
Figure 30 Sankey diagram of interview codes interaction	108
Figure 31 Quantified outcomes from four of the eight use cases	116
Figure 32 SDG distribution across eight use cases	116
Figure 33 Word cloud of CFG transcript data	120
Figure 34 Word cloud of CFG transcript-coded data	120

Figure 35 Sankey diagram of sentiment analysis and codes from CFG	121
Figure 36 DSR knowledge contribution framework, adapted from Gregor and Hevner (2013:9).....	143

LIST OF ABBREVIATIONS

ACD — Abstract, Contextualise and Design (the methodology used to develop the thesis artefacts)

CFG — Confirmatory Focus Group

DSR — Design Science Research

ES — Environmental Sustainability

IE — Industrial Engineering

IISE — Institute of Industrial and Systems Engineers

NRBV — Natural-Resource-Based View

PWTA — Pareto Weighted Thematic Analysis

RBV — Resource-Based View

SCA — Sustainable Competitive Advantage

SDG — Sustainable Development Goal

SLR — Systematic Literature Review

TD — Transdisciplinary / Transdisciplinarity

UCA — Use Case Analysis

VRIO — Valuable, Rare, Inimitable, Organised

Chapter 1

Introduction

1 Introduction

1.1 Background

The evolution of human development has elevated societal well-being by ensuring economic growth (Ranis, 2004). These anthropogenic activities from societal development have imposed negative effects on the environment for many years (Das, 2020). Many of the modern advancements can be attributed to the industrial revolutions that began in the 1800s.

The first three revolutions advanced technologies, created new opportunities and redefined work methods. Specifically, the First Industrial Revolution (from the 1760s) introduced mechanisation and steam power, the Second Industrial Revolution (from the 1870s) introduced mass production and electrification, and the Third Industrial Revolution (from the 1970s) introduced computing and automation. The Fourth Industrial Revolution has reshaped the manner in which technology influences the economy and society by also emphasising higher technical education and forming closer links between scientific advancements with industrial progress (Fremdling, 1997). It has enforced a new *modus operandi*. Despite its benefits, the emissions and energy usage across technology life cycles negatively affect the environment, simultaneously contributing to global warming (Elheddad *et al.*, 2021). According to Sperotto (1994), these revolutions produced the conditions that led to the formation of the Industrial Engineering (IE) profession.

The field of IE has inspired new solutions, strategies and problem-solving methods that have yielded noteworthy profits, effectiveness, efficiency and productivity in a multitude of industries (Darwish & Van Dyk, 2016; Haleem *et al.*, 2024; Mangaroo-Pillay & Roopa, 2021; Salvendy, 2001). Effectiveness considers the achievement of organisational goals that are assessed on a strategic level (Noesgaard & Ørngreen, 2015). Efficiency is most commonly understood as the ratio of actual output relative to a standard, whereas productivity is simply concerned with the ratio of output to input (Jacobs & Chase, 2018). This distinction welcomes derivatives of efficiency that focus on specific goals or objectives within organisations.

The IE discipline is built on a foundational knowledge domain that facilitates the creation of value and sustained growth for a diverse set of organisations. Moreover, the IE discipline welcomes the development of new ideas, theories and strategies that improve processes and ensure increased levels of productivity and efficiency using balanced value creation (Darwish, 2018).

Arguably, the conditions that led to the formation of the IE profession and the environmental degradation (imposed by each revolution) reveal an association between the IE discipline and the environment (Kasa, 1973; Mert *et al.*, 2025). In theory, this discipline should be able to identify and resolve negative effects on the environment. IE instincts should allow industrial engineers to remedy the effects of the very cause of their existence. This notion is further supported by Darwish (2018:177) who discusses disharmonious industrial thinking, stating that “... *one cannot deny the massive environmental and social degradation caused by this type of thinking by Industrialists and, to some extent, Industrial Engineers of the 18th to 20th century. In fact, some of the negative effects remain to the modern day. Yet, it is arguable that Industrial Engineering (IE) has also contributed to the problem as well; by making things faster, cheaper and better it also increases their consumption.*” Such a notion further accentuates the need for IE to take responsibility in resolving environmental challenges.

The association between improvement strategies and environmental impact vary per application. For example, Just-in-Time (JIT) ensures limited inventory with increased transport between stages of production and supply chain stakeholders. Unfortunately, this increases transport emissions (Roopa *et al.*, 2020; Zokaei *et al.*, 2017). On the other hand, striving for zero inventory and one-piece flow can alleviate auxiliary systems and their energy needs (Verrier *et al.*, 2016).

The environment is home to society and the economy (Darwish, 2018). This intertwined system is designed such that any change or activity in one facet implicates the other. For this reason, sustainability aids in achieving balance and acts as a means of achieving harmony between these facets. The term sustainability derives from the Latin word '*sustenere*', and describes a contribution to sustainable development concurrently creating social, economic and environmental benefit (Hart, 1997). Environmental sustainability remains a topic of global concern (Asha *et al.*, 2023; Gore, 2008). Environmental sustainability considers the theory and practices that prioritise environmental preservation and prevent degradation (Morelli, 2011; Qi *et al.*, 2020). For countries all over the world, environmental practices are of utmost importance and will continue to become progressively relevant (Roman, 2017).

One of the most recent strides in establishing far-reaching transformation is that of the Sustainable Development Goals (SDGs) developed by the United Nations (United Nations, 2015). The 17 SDGs can be further categorised into the three pillars tied to economic, social and environmental prosperity.

The environmental pillar encompasses the following goals:

- a. SDG 6: Clean water and sanitation
- b. SDG 7: Affordable and clean energy
- c. SDG 12: Responsible consumption and production
- d. SDG 13: Climate action
- e. SDG 14: Life below water
- f. SDG 15: Life on land

Each SDG has a set goal and objective with specific outcomes that promote economic sustainability, while ensuring economic growth and societal wellbeing. Environmental sustainability is an important component when designing solutions to current and future problems (Vezzoli & Manzini, 2008). In some cases, the environment can also serve as a source of inspiration for innovation. The work of Fayemi *et al.* (2014), used inventive methods from TRIZ (Theory of Inventive Problem Solving) to link with generic steps in problem solving and biomimetic methods.

Organisations are tasked with simultaneously pursuing environmental sustainability (ES) targets while maintaining a sustainable competitive advantage. A sustainable competitive advantage is achieved when organisations embrace sustainability in their strategy used to compete in the market (Sharma & Gupta, 2024; Tiwari *et al.*, 2020; Waqas *et al.*, 2021). The traditional competitive advantage defines attributes that enable organisations to outperform their competitors using core differentiators (Maráková *et al.*, 2023). For some time, a sustainable competitive advantage has remained a cornerstone of strategic thinking (Coyne, 1986; Hart, 1997; Rodriguez *et al.*, 2002). According to Pirela *et al.* (2024), strategic thinking evaluates the environment, opportunities and threats to formulate long-term plans for success (Pirela *et al.*, 2024). Instances exist where a competitive advantage has explored green innovation and sustainable supply chains

(Chang, 2011; Markley & Davis, 2007), without considering an all-encompassing environmentally considerate strategy that transcends organisations and institutions using IE.

Green innovation seeks to reduce environmental impacts by focusing on eco-innovation solutions that improve environmental and economic performance (Meidute-Kavaliauskiene *et al.*, 2021). Sustainable supply chains are designed such that the long-term economic performance is maximised while concurrently minimising the negative environmental and social impacts at play (Varsei, 2019). It is often believed that strategy is used to achieve a sustainable competitive advantage regardless of industry or sector (McGrath, 2013). For any endeavour, a well-defined strategy aids in achieving a sustainable competitive advantage, often influenced by technological and environmental challenges (Catalin & Anca, 2015). In this research, IE and ES will serve as the core focus areas.

1.2 Research focus

This research will position itself within the IE knowledge domain as a point of departure. The Institute of Industrial & Systems Engineers (IISE) (2021b) defines this Body of Knowledge as a taxonomy representation, as illustrated in Figure 1.

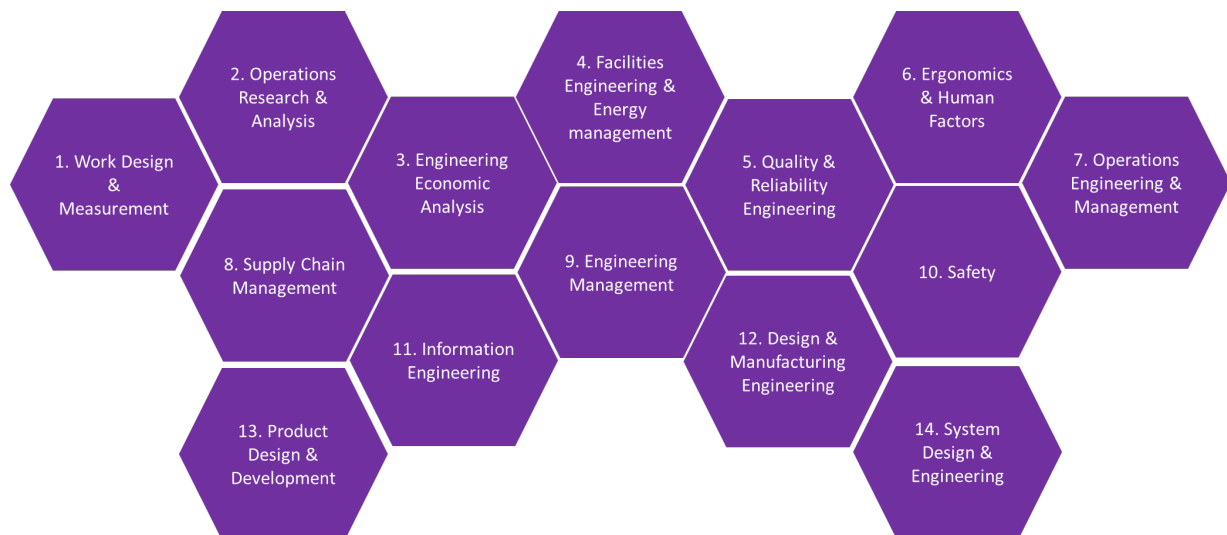


Figure 1 Industrial and Systems Engineering Knowledge Areas adapted from (IISE) (2021)

The vast array of these knowledge areas demonstrates how the fundamentals of IE appeal to the multidisciplinary environment in which the discipline thrives. Another popular representation of the knowledge and capabilities of the IE profession is that of Salvendy (2001) which uses set domain definitions. This is encapsulated in Figure 2.

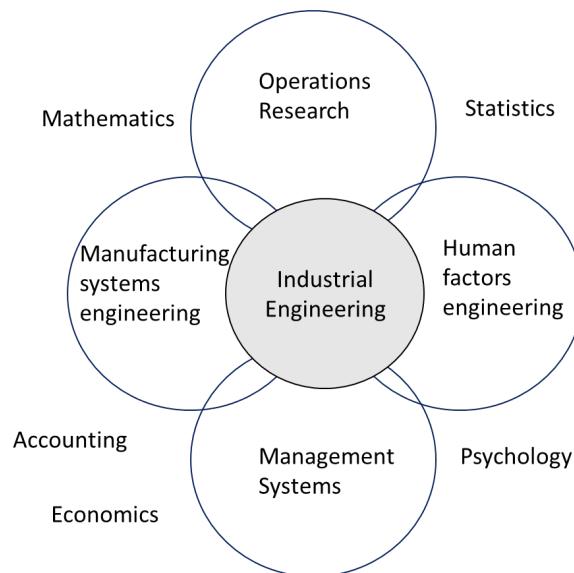


Figure 2 IE domain definitions from Salvendy (2001)

The knowledge areas and domain definitions from figures 1 and 2 allude to a diverse perception and concept boundary regarding IE. As a means of bringing certainty to the knowledge area pertaining to IE thinking, Darwish (2018) formalised the IE identity for the knowledge era. A core artefact is an Industrial thinking systemigram which calls on the professional to understand ecological and social system impacts more stringently.

The formulation of adoption models and artefacts for sustainable practices is encountered in the literature. Anthony *et al.* (2017) formulated a model for adopting sustainable practices, specific to software-based organisations. Their study revealed variables, green strategies and drivers that influence sustainability and the adoption of sustainable practices.

Developed countries face easier environmental transitions, as opposed to developing countries, due to their cleaner energy mix, technological and regulatory advantages, and ability to outsource polluting activities to developing countries (Benzerrouk *et al.*, 2021; Wieczorek, 2018). South Africa is the developing country which faces the most significant environmental challenges on the African continent, given its development (Darkoh, 2009). South Africa has become a signatory to the Kyoto Protocol in a conscious environmental effort, pledging to control Greenhouse Gas (GHG) emissions (Gohar & Shine, 2007). Policymakers also formed the Paris Agreement, aiming to hold the global average temperature increase below 2°C. Developing countries are at the onset of establishing their economies, providing infrastructure and stability for future growth. However, such countries tend to have intensified environmental degradation due to CO₂ levels as opposed to developed countries (N'dri *et al.*, 2021). According to N'dri *et al.* (2021), the cost of cleaner energy sources encourages the use of non-renewable energy sources during the early stages of their economy.

The Organisation for Economic Co-operation and Development (OECD) is an institution that provides an independent analysis and statistics for policymakers. This aids in improving economic growth and social wellbeing across the globe. As of 2007, the OECD council declared South Africa as one of the five key partners to the OECD with Brazil, China, India and Indonesia. South Africa is the most burdensome energy consumer and emissions emitter on the continent (Ndoricimpa, 2017). Moreover, the country also possesses the highest CO₂ emissions per capita. Carbon tax, clean energy funding and

other efforts have been initiated as a national response to these challenges. South Africa will be used as a case study through the analysis of environmental performance levels, environmental needs, opportunities and environmental sustainability. South Africa, much like other developing countries, must ensure economic growth by increasing employment and reducing poverty and inequality (Ndoricimpa, 2017).

To showcase the development of concepts and theories associated with IE, some of the research conducted in the field of Industrial and Manufacturing engineering is considered as search criteria. Scimago results are catered for, using the country rank feature from the platform, which explored the research success across all parts of the world. Although this neglects population density and non-english publications, the results reveal the following research publications, citations and H-index per country. A portion of the top 10 and first African country are showcased in Table 1. This table was elaborated by the author, compiled from country-rank data obtained from the Scimago Journal & Country Rank platform.

Table 1 Scimago rankings on research publications per region from 1996 to 2023

Rank	Country	Citable documents	Citations	Self-citations	Citations per document	H-index
1	United States	14617353	564191398	226496389	33,26	3213
2	China	11461281	178312168	107610366	15,26	1455
3	United Kingdom	4196657	158900978	31829276	31,22	2048
4	Germany	3931535	121470423	25987033	28,07	1797
5	Japan	3442416	76400180	17329253	21,05	1364
6	India	3010235	44912652	15797988	13,44	925
7	France	2677893	82008442	14588890	28,09	1604
8	Italy	2417621	68905437	14692274	25,52	1416
9	Canada	2275692	82451695	12443100	32,01	1659
10	Australia	1865552	65188977	11200952	30,37	1475
11	Spain	1935060	52225630	9921493	24,64	1303
12	Russian Federation	1780170	17406739	5710763	9,49	806
13	South Korea	1660476	35304573	5800194	20,56	1004
14	Brazil	1435346	25517390	7341141	16,7	844
15	Netherlands	1268424	53669901	6821752	37,64	1471
16	Switzerland	959406	40611905	4403706	38,14	1369
17	Poland	974258	15898395	3341450	15,41	792
18	Turkey	929722	15238939	2945992	15,15	647

Rank	Country	Citable documents	Citations	Self-citations	Citations per document	H-index
19	Iran	933139	15639174	4357975	16,19	541
20	Sweden	877676	33527896	4064825	34,79	1232
21	Taiwan	889288	18681477	2739387	20,14	738
22	Belgium	708472	25838558	2702915	32,92	1134
23	Denmark	548995	22339602	2500563	36,59	1081
24	Austria	533998	17342330	1813045	29,17	937
25	Malaysia	524435	8383643	1604620	15,09	559
26	Israel	489626	17125142	1873165	31,52	962
27	Portugal	474462	11887422	1689698	22,59	739
28	Mexico	481535	8841868	1534261	16,99	641
29	Hong Kong	464238	15790931	1525012	31,37	863
30	Norway	443666	14946021	1809261	29,96	896
31	Czech Republic	474100	8643140	1453179	17,35	667
32	Finland	452432	15592944	1846816	31,44	897
33	Saudi Arabia	470933	9340350	1547751	19,02	618
34	South Africa	433104	9916908	1802302	20,26	702

From Table 1, South African research is ranked 34th and offers opportunities for more research. According to these Scimago rankings, South Africa is the highest-ranked African country with regards to the research outputs in IE. More interestingly, on average each research paper is cited more often than some of the higher-ranked countries, alluding to great interest in the research. This further attests to the need for more research into, and closer investigation of South African research, as the leading research country on the continent.

Organisations strive to make a profit and remain competitive in the industries or sectors they compete in by offering the same benefits as their competitors at a lower cost, or the same product with superior features (Wang *et al.*, 2011). As previously discussed, efforts have been made to ensure a sustainable competitive advantage, which considers the use of sustainability practices to enhance business offerings (Srivastava *et al.*, 2013). In South Africa, this has been explored in the retail sector in the marketing space (Dos Santos, 2009), but not within IE contexts.

To further contextualise the focus of this research, a minimal system representation is encapsulated in Figure 3 using the literature informed understanding of the research. The minimal system is a form of concept mapping that reveals key elements needed to form a system. Further to this, it also serves as a crucial representation defining complexity

and improving engineering processes by reducing size and redundancy Schindel (2024). It is read by following flow logic between system interactions.

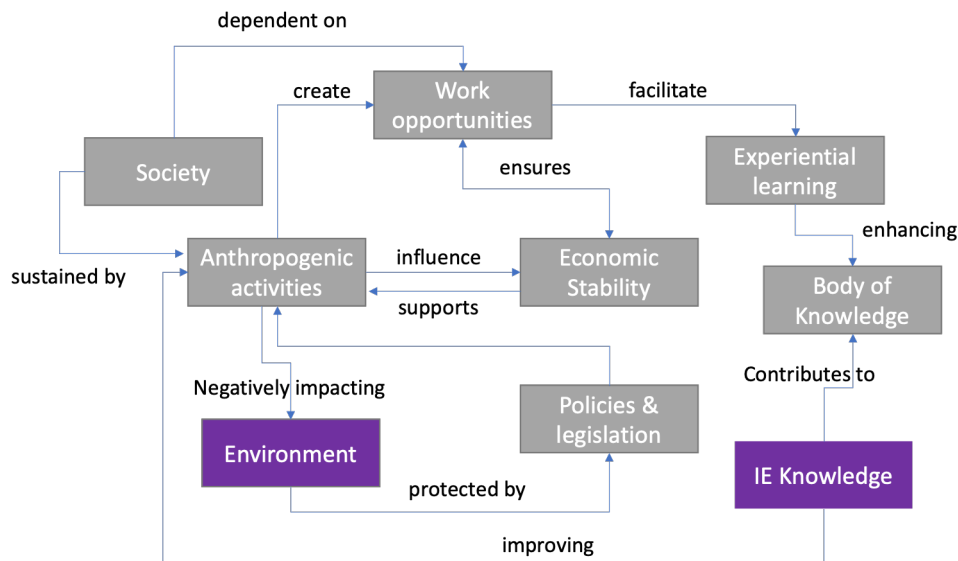


Figure 3 Minimal System Representation of research focus [Researcher's own work]

The minimal system demonstrates some components that will affect the scope of this research, along with their interactions. Society is sustained by anthropogenic activities that create economic sustainability and relate to an organisation trying to maintain a sustainable competitive advantage. This venture creates work opportunities that facilitate forms of experiential learning, which is later formalised as knowledge, which adds value to academia and industry and feeds back into this minimal system representation. Some of this tacit knowledge can be attributed to IE and environmental sustainability, which currently share a limited formal association with little to no guidance on how to achieve a sustainable competitive advantage. This results in fragmented knowledge between industrial engineering and environmental sustainability domains. These anthropogenic activities are controlled by various policies and legislation which support society and create sustained growth. This contextualisation is used to demonstrate the opportunity identified in this study.

For the purposes of this research, several terms are pertinent to define and demonstrate their use for conceptual consistency. The first being firms and organisations, while many a time considered distinct (Robé, 2022), Le Grand and Roberts (2021) and Van den Bergh (2004) argue that organisations and firms can be used interchangeably due to the complexity of individual motivations and the potential for hybrid organisations that blend social and economic goals. Especially in industrial organisation when focused on nature, existence and co-ordination, Buckley and Michie (1996) further motivate this. Hence, this research will use these terms interchangeably. The two formal disciplines associated with this research pertain to Industrial Engineering, as defined in sections 1.1 and 1.2, alongside as the broader classification of environmental sustainability detailed in section 2.3 from Chapter 2. This research formalises knowledge components in Chapter 6 using the business execution levels as a knowledge taxonomy. For the unit of analysis, SCA forms inherently within firms (organisations). To bridge between the theoretical to real world setting, it becomes imperative to situate the SCA theory within national levels. The generalisability begins with South Africa as a case study, further strengthened by

generalisability claims. Further forms of strategy, theories, and methods and practices are also defined throughout the thesis.

1.3 Research gap

South Africa has a high resource intensity and environmental risk, which can impact firm resilience and market position, as discussed by Chipunza and Mupani (2019). This research argues that by applying IE thinking, environmental practices can be improved in order to reduce waste and strengthen an organisation's competitive advantage. In a similar vein, South Africa also has one of the poorest energy mixes, calling for urgent integrated responses for grid stability and reduced environmental impact (Klausbruckner *et al.*, 2018). This high resource intensity with industrial growth for the country suggests high energy and material consumption which burdens the environment (Conradie, 2010; Wiese *et al.*, 2015). For Small and Medium Enterprises (SMEs), remaining competitive in local and export markets warrants integrated models that tie in productivity and environmental practices (Thekkooote, 2022).

Current forms of a sustainable competitive advantage (SCA) in South Africa have yet to integrate knowledge from IE and environmental sustainability in the South African automotive sector and steel industry (Wiese *et al.*, 2015). Research in the country has been able to reduce waste, improve resource efficiency and become more price competitive by lowering variable costs (Bag *et al.*, 2023; Weaich *et al.*, 2024). In SMEs, it was found that the long-term competitiveness of smaller firms is more optimistic when lean practices with green manufacturing techniques are employed (Thekkooote, 2022). In the automobile industry, strides by Davies and Van der Merwe (2016) have conceptualised environmental mapping tools within IE contexts. Within the sector, a popular vehicle manufacturer yielded business success by integrating aspects from best-practice business models, lean manufacturing, and green manufacturing (Bag *et al.*, 2023).

One way in which sustainability challenges can be resolved is to employ Transdisciplinary (TD) research (Angelstam *et al.*, 2013). This collaborative research approach draws on various knowledge domains with multiple stakeholders from academic or non-academic spheres (Belcher *et al.*, 2016). TD is typically segmented into the co-planning, co-production and co-implementation of impact that solves complex problems systematically by integrating knowledge from different disciplines (Wada *et al.*, 2020). According to the work from Polk (2015), co-production is based on joint ownership, responsibility and commitment from all stakeholders that involve inclusion, collaboration, integration, reflexivity and usability. Furthermore, this phase entails the formulation, generation and evaluation of the problem, solution and impact. Researchers working in South Africa attest to sustainability challenges requiring TD responses, since single-discipline solutions do not suffice (Hemström *et al.*, 2021; Weaich *et al.*, 2024). Furthermore, it is also suitable to apply TD so as to align contested goals, interdependent outcomes and multi-stakeholder complexity interacting across varying levels (Paterson *et al.*, 2010). In addition, the highly integrated supply chain and ecosystem that supports all anthropogenic and business activities calls for integrative analysis and understanding beyond disciplinary boundaries as discussed by Lüdeke-Freund *et al.* (2017). To spur on academic research in the country, this must carefully combine industry expertise with societal knowledge. To better align solutions with local values and implementation prospects, co-production is pivotal (Brent *et al.*, 2008; Paterson *et al.*, 2010).

A close association to TD is that of Transdisciplinary Engineering. This research argues that Industrial Engineering is able to execute TD research. According to Peruzzini *et al.*

(2020), transdisciplinary Engineering as extends beyond technical disciplines to combine “natural sciences, applied sciences, social sciences and humanities. This implies industrial engineering is evolving toward this transdisciplinary model, particularly in Industry 4.0 contexts, rather than being inherently transdisciplinary. Using this stance, the research will argue and explore industrial engineering and its capability in TD research orientated problem solving.

Even though Somerville and Rapport (2002) have produced pivotal work on recreating integrated knowledge, several shortcomings are identified. These include These shortcomings include conceptual ambiguity and theoretical fragmentation, a lack of concrete methodological frameworks, underestimation of institutional and structural barriers, insufficient attention to power dynamics and knowledge asymmetries, and challenges regarding assessment and academic credibility. In addition to this, the promising track record of employing IE and environmental sustainability, limited research has explored employing TD research which integrates this for more holistic solutions (Shrivastava *et al.*, 2013; Stock & Burton, 2011). The adoption of the aforementioned work has only solved sustainability challenges using a disciplinary perspective, which creates trade-offs between profitability and environmental conformance (Zokaei *et al.*, 2017). For complex ecological models, this trade-off can involve modularity and integration when applying techniques from one discipline to another (Vedder *et al.*, 2024). Therefore, integration becomes crucial. The complex systemic and wicked nature of this research finds itself at the intersection between environmental sustainability, SCA and TD production phases. In essence, it links the sustainability dimension to forms of disjointed knowledge from SCA, IE taxonomies, and TD production phases. To better delineate and position the research gap, Figure 4 depicts the shortcomings and focus of this research using the context already offered in this chapter. The delineations are structured around both indirect and direct associative sources of knowledge, information, and topics related to this research topic ((IISE), 2021a; Barton & Gutiérrez-Antinopai, 2020; Roopa *et al.*, 2024; Salvendy, 2001; Sołoducho-Pelc & Sulich, 2020; Wada *et al.*, 2020).

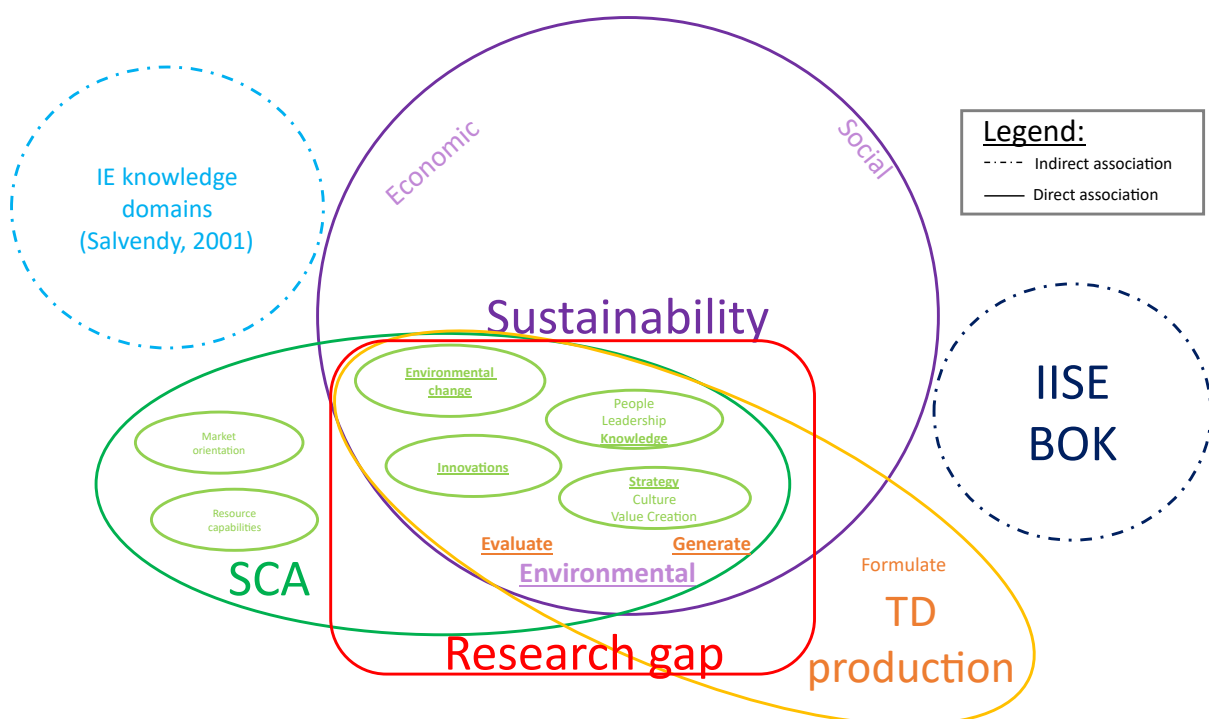


Figure 4: Research gap delineation

The aforementioned IISE BOK and IE domains share an indirect association, since they give recognition of the IE identity but neglect sustainability narratives. The sustainability dimension considered in this study entails environmental with economic and social dimensions falling outside the scope of this study. By recognising the three TD production phases mentioned by Polk (2015), the evaluation and generation phases are employed. Since the formulate phase in TD production is context-sensitive and application-oriented, traditional formulation requires less focus (Van Manen, 2001; Zierhofer & Burger, 2007). For added complexity, the formulation of the research problem therefore features in this chapter. Finally the SCA considerations explore aspects from four of the six factors derived by Sołoducho-Pelc and Sulich (2020). Environmental change, Knowledge, Innovations and Strategy have been included. Market orientation and resource capabilities extend the focus towards a general analysis, which should feature as SCA considerations after the SCA has been defined. South Africa is considered as the leading African country in research that could boost African competitiveness, research and rankings.

1.4 Research opportunity

IE finds itself at the forefront of innovation with a subconscious solution space comprising various theories, strategies, tools and methods that apply to numerous sectors (Moynihan, 2021). The nature of these solutions appeals to a broad range of problems, as does the value and contribution of this discipline to achieving a sustainable competitive advantage which is currently under-explored (Sachdeva *et al.*, 2019). The path to a sustainable competitive advantage remains unclear, with increased pressures to comply with environmental policies and legislation so as to meet new environmental performance measures. The challenges experienced in South Africa are complex and require systemic problem-solving. One approach is to call on the knowledge belonging to IE and ES for a sustainable competitive advantage. Such an exploration welcomes higher sustainability objectives being met within organisations while remaining competitive. It also suggests TD production phases to harness the potential of integrating IE and ES.

1.5 Problem statement

Knowledge from IE and ES domains currently lacks a formal, visible and intuitive classification without a transdisciplinary integration to successfully achieve an SCA in South Africa.

1.6 Research aim, questions and objectives

Researchers can either identify a research gap or problematise the existing understanding of literature or its assumptions (Alvesson & Sandberg, 2011; van Aken & Berends, 2018). This study is focused on contributing to the debate on the lack of a formal classification of IE and ES research. Furthermore, it problematises literature by evaluating this lack of visibility and classification imposing challenges in achieving a sustainable competitive advantage in South Africa. The following research aim and objectives are formulated to address the problem statement previously defined.

1.6.1 Research aim

This study strives to improve the formalisation, visibility, classification, or transdisciplinary integration of IE and ES knowledge to achieve a SCA in South Africa.

1.6.2 Research questions

To advance the research, the following research questions are posed.

Central research question: How can IE knowledge be integrated with ES to ensure an SCA in South Africa?

Sub research question 1: What is the relationship between IE knowledge and ES knowledge?

Sub research question 2: Which knowledge components can be retrieved from industry and academia to achieve an SCA in South Africa?

Sub research question 3: What type of design methodology can be created for TD problem solving?

Sub research question 4: How can a framework be designed and tested to ensure IE knowledge facilitates an SCA for South Africa?

1.6.3 Research objectives

By constructively evaluating the research question, set objectives emerge, namely to:

1. Identify and categorise IE and ES knowledge from literature.
2. Identify IE and ES knowledge applied in South Africa that ensures an SCA.
3. Create a design methodology for transdisciplinary problem solving in South Africa.
4. Design a framework that integrates the preceding IE and ES knowledge created.
5. Evaluate the ability of the framework to facilitate an SCA in South Africa.

1.7 Research design

Design Science Research (DSR) was used to design the research, using structured elements taken from the layers of the research onion. The research study is composed of four distinct stages, most strongly linked by the objectives previously presented. The application of the research onion, DSR and a set of research techniques is dedicated to Chapter 3. The research design facilitates the integration of Systematic Literature Review (SLR) and interview data subjected to Pareto-Weighted Thematic Analysis. A design methodology for TD artefacts in South Africa is then developed. Using the configured methodology, a TD artefact for an SCA is evaluated with a Use Case Analysis and Confirmatory Focus Group. This supports the exploratory nature of this research.

1.8 Novelty and contribution

This research amalgamates various strategies, theories, methods and practices aligned to a sustainable competitive advantage. This provides a stronger association with the partially connected realms of IE and environmental sustainability. This research gives recognition to the knowledge and ideas the IE profession has had on various industries and countries. More specifically, this research will uncover the value of this knowledge in facilitating a sustainable competitive advantage for South Africa. This research is able to integrate the knowledge and gain from IE and ES domains within TD contexts using the co-generate and evaluate phased of TD production focusing on. This research beckons transdisciplinary knowledge creation due to the dichotomy considering academics and practitioners from multiple industries which are educated in IE and/or environmental sustainability. This venture attests to transdisciplinary knowledge creation for a sustainable competitive advantage. It brings IE closer to sustainability challenges by substantiating its contribution using the three business execution levels (strategy, tactical and operational levels). In essence, the research pioneers transdisciplinary synthesis techniques to redefine IE as a catalyst for environmental sustainability, even so much as a sustainable competitive advantage. Furthermore, this thesis will introduce new

questions, new ideas and new strategic means of achieving a sustainable competitive advantage by reflecting on the knowledge that IE and environmental sustainability offer.

1.9 Chapter outline

The thesis will be structured as follows:

- Chapter 1 - Introduction
- Chapter 2 - Literature Review
- Chapter 3 - Research Design
- Chapter 4 - Exploring IE Knowledge and Environmental Sustainability (**Article 1**)
- Chapter 5 - Identifying Harmony between IE and Environmental Sustainability in South Africa (**Article 2**)
- Chapter 6 – An Industrial Engineering inspired lighthouse model for transdisciplinary problem solving and sustainable development in South Africa (**Conference paper 1**)
- Chapter 7 – A transdisciplinary pyramid waterfall fountain model for a sustainable competitive advantage (**Manuscript 1**)
- Chapter 8 – Analysis of SLR and interviews
- Chapter 9 – Use Case Analysis (**Conference paper 2**)
- Chapter 10 – Confirmatory Focus Group
- Chapter 11 – Discussion
- Chapter 12 – Conclusions, novelty, limitations and recommendations

1.10 Chapter summary

This chapter provides context around the purpose and nature of this study. It also delineates the research by providing the research problem, aim, questions and objectives. The research gap is visualised, showing interaction with pertinent subject matter. There is mention of DSR as the methodology tied to the research onion, further discussed in Chapter 3. The appropriate ethical considerations and novelty of this research have also been outlined. The next chapter serves as the literature review aligned to topics which concern the nature of this study. The following chapter outlines the pertinent literature associated with research of this nature.

Chapter 2

Literature Review

2 Literature Review

2.1 Introduction

This section serves to further contextualise the study by providing more insight into the theory relevant to the nature of this study. A representation of all relevant theory and the subsection flow is illustrated in Figure 5.

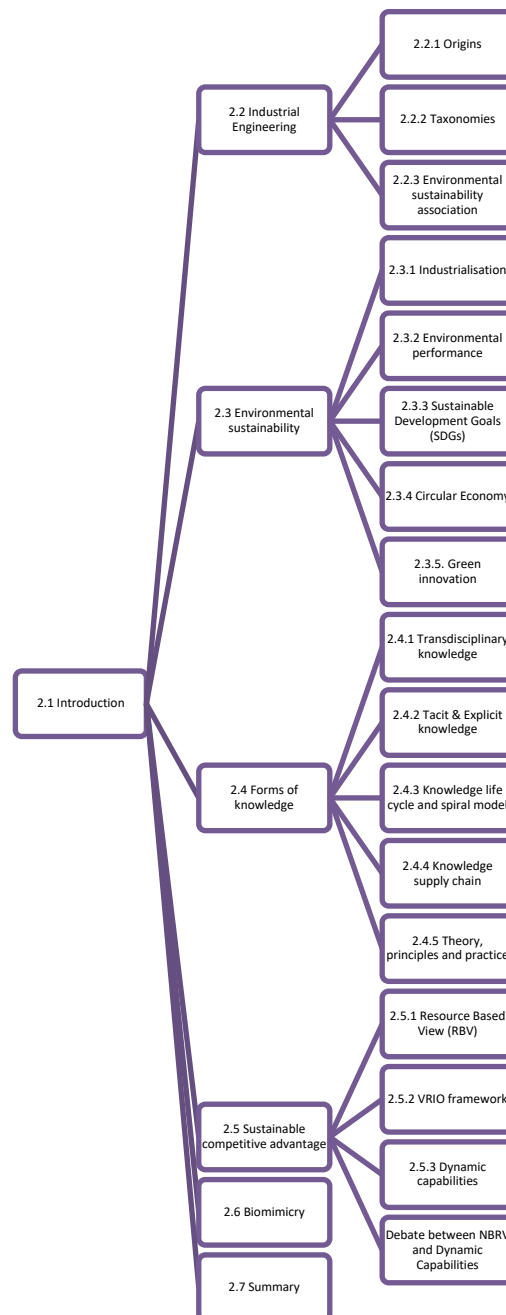


Figure 5 Literature Review Overview

The structure of the literature review only introduces pertinent forms of concepts that are associated with parts of the study later incorporated in the research design (chapter 3), publications, discussions and conclusions. Theoretical context and literature thus features across these chapters, extending beyond this chapter.

2.2 Industrial Engineering (IE)

2.2.1 Origins

The IE profession has emerged as a discipline that has brought about innovation, creative problem solving and advances in societal systems (Mangaroo-Pillay & Roopa, 2021). IE is recognised for the productivity gains obtained in more organisational and streamlined procurement, inventory, quality and control systems by redesigning machines and tools for higher accuracy and efficiency (Bailey & Barley, 2005). It has evolved into a domain that seeks to balance value as a master of integration (Darwish & Van Dyk, 2016).

The profession was formed in response to the operational needs that grew during the first industrial revolution. It soon became apparent that specialised knowledge was required to sustain operations in manufacturing and service environments within society.

The analogy of the profession can be made with an Aspen tree, as used in the work of Darwish and Van Dyk (2016) who present a tree model for the IE identity, with the fundamental belief that balance is the greatest value of the profession. It has become the basis of manufacturing engineering, management science and systems engineering (Li *et al.*, 2022). For some time, the IE profession has worked on understanding continuous systems (Capehart, 1977). Furthermore, the profession prides itself on its integration of various subsets that belong to any system. Most arguably, the definition commonly used to describe the profession stems from the Institute of Industrial and Systems Engineers (IISE, 2023):

“Industrial Engineering is concerned with the design, improvement and installation of integrated systems of people, material, information, equipment and energy. It draws upon specialised knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems.”

This multidisciplinary field has its roots in the industrial revolution and has continued to grow and mature with each succeeding revolution inspired by the fields of scientific management, operations research and industrial and systems engineering (Sperotto, 1994).

The efforts of IE appeal to a broad range of industries. The implications of IE have empowered and spurred the development of various mental models in the fields of enterprise excellence, quality and safety management systems, healthcare and supply chain sustainability, to mention only a few (De Vries, 2016; du Plessis *et al.*, 2022; Gerolamo *et al.*, 2014; Sharma *et al.*, 2021).

IE is recognised for the productivity gains obtained in more organisational and streamlined procurement, inventory, quality and control systems by the redesigning of machines and tools for higher accuracy and efficiency (Bailey & Barley, 2005). It has evolved into a domain that seeks to balance value a master of integration (Darwish & Van Dyk, 2016).

In South Africa, some of the current challenges for the IE profession mentioned by Schutte *et al.* (2016) are that South Africa has transformation challenges which call for increased focus. In addition, more work can be done to have IEs embrace new challenges posed by the information age and to remain in touch with recent skills.

The origins of this discourse extend beyond engineering into the broader history of sustainable development thinking itself. Jacob (2025) traces the evolution of sustainable development as a global agenda through six historical stages, from its earliest conceptual sprouting through to its present form encompassing environmental, social, economic and governance pillars. Situating the IE profession and its more recent engagement with sustainability against this longer historical helps explain why formal integration between IE and environmental sustainability has, until recently, remained comparatively underdeveloped.

2.2.2 Taxonomies

As previously discussed in Chapter 1, two taxonomy models portray the nature of IE, by illustrating the various knowledge domains (Salvendy, 2001), as well as the application areas using the bodies of knowledge ((IISE), 2021a).

The IE knowledge domains speak to the traditional foundations that led to the formation of the profession (Salvendy, 2001). While the work and nature of IE are indeed challenging to classify, this model demonstrates the fundamental theory domains from which IE draws insight to creatively design innovative solutions to real-world problems. This shows a good balance between the quantitative and hard sciences rooted in mathematics and statistics, which is supported by economic considerations through a basic understanding of accounting and economics.

Closer to the core of IE is operations research which emerged from World War 1, manufacturing systems engineering steered by industrial revolutions as well as advancements in technologies and, of course, management systems and human factors engineering. The psychology feeds into human factors engineering which considers the human aspect, a core attribute that differentiates Industrial engineers from other disciplines. As also mentioned in chapter 1, another taxonomy model is the IISE (Institute of Industrial and Systems Engineers) Body of Knowledge (BOK).

The IISE BOK was formed after a 3-year consultation within the IISE. This gives great recognition to the nature of work in clearer detail than the theory domains. This taxonomy represents the fundamentals of Industrial and Systems Engineering to demonstrate mastery of the field when designing integrated solutions.

Systems engineering has become synonymous with Industrial engineering (Parnell *et al.*, 2022). The Industrial and Systems Engineering BOK was first developed in 2010 with the first version made accessible in 2016 (Bidanda, 2022). This taxonomy model boasts the success of industry and academia collectively engaged in the design and development process. The IISE Body consists of 14 knowledge areas. When reflecting on the IISE BOK and the knowledge domains defined by Salvendy (2001), they both give recognition to the diverse application areas and contribution Industrial engineers have, which link with the traditional knowledge areas. Despite the multidisciplinary nature of IE being evidenced, a major shortcoming is that none of the ontology frameworks in the literature explicitly link with Environmental Sustainability.

This gap has begun to attract scholarly attention beyond South Africa. de Oliveira Neves *et al.* (2024) constructed a taxonomy of sustainability conceptualisations specifically for industrial production processes, demonstrating that engineering frameworks can be extended to embed environmental criteria formally rather than treating them as a reaction. Their taxonomy becomes an example of how IE's own bodies of knowledge might be restructured to close the sustainability challenges.

2.2.3 Environmental sustainability association

What is perhaps of more interest is that neither of these two famous IE taxonomy models explicitly speak to environmental sustainability. This is a deficiency or neglected aspect that IEs have not formally addressed and is the basis of this research exploration.

A core responsibility of the Engineering Council of South Africa (ECSA) is to regulate and hold engineering activities in accordance with the Engineering Profession Act of 2000 (RSA, 2000). In Act No. 46, a code of conduct for registered people detail rules specific to ethics and the environment. Under the environment, a registered person must practice sustainable development to best protect and preserve the environment. A shortcoming is that there is no specific mandate on solutions to address climate change within engineering practices. When contrasting this globally, the USA, UK and Australia reply on a mix of regulations. For example, the PE licenses in the USA speak to public health and safety, insinuating ES (Michelfelder & Jones, 2013).

Industrial engineers are more accountable for environmental degradation despite operational gains created in organisations (Hoque *et al.*, 2018). The reason for this is twofold: the first being that they may have spurred environmental degradation behaviour, and the second is the ability of the profession to seek productivity improvements that can be directly translated into environmental performance (Darwish, 2018; Mangaroo-Pillay & Roopa, 2021). Buzacott (1984) argued that IE lacks cohesiveness and entails low-level engineering content. This critique has long since been contested by the emergence of specialised areas within IE and the inclusion of all ranges of engineering content.

Advances in IE research have started tackling environmental challenges in developing countries. One such effort was demonstrated by researchers who explored the use of software to aid in supply chain supplier selection processes and sustainability assessments concerning reverse logistics (Abdallah & El-Beheiry, 2022; Toktas-Palut *et al.*, 2022). The need for infrastructure development led Al-Ghamdi *et al.* (2023), to the exploration of environmental factors needed for sustainability concerning the quality of urban life. A hierarchical assessment model was developed that emphasises eco-friendly indicators for sustainable urban life.

2.3 Environmental sustainability

The term sustainability is concerned with the use of resources at a rate that does not exceed regeneration, ultimately preserving said resources. Our understanding of the interconnectedness of sustainability dimensions has evolved. The forms of sustainability consider the economy, the society and the environment. This was first considered completely siloed (Mickey Mouse model), which was later understood to have forms of interaction. This led to the Venn diagram 'triple bottom line' model which was enhanced and is now considered the bullseye model which is not cognisant of the embedded economy which functions within social constructs within a particular environment. Figure 6 depicts this evolved understanding.

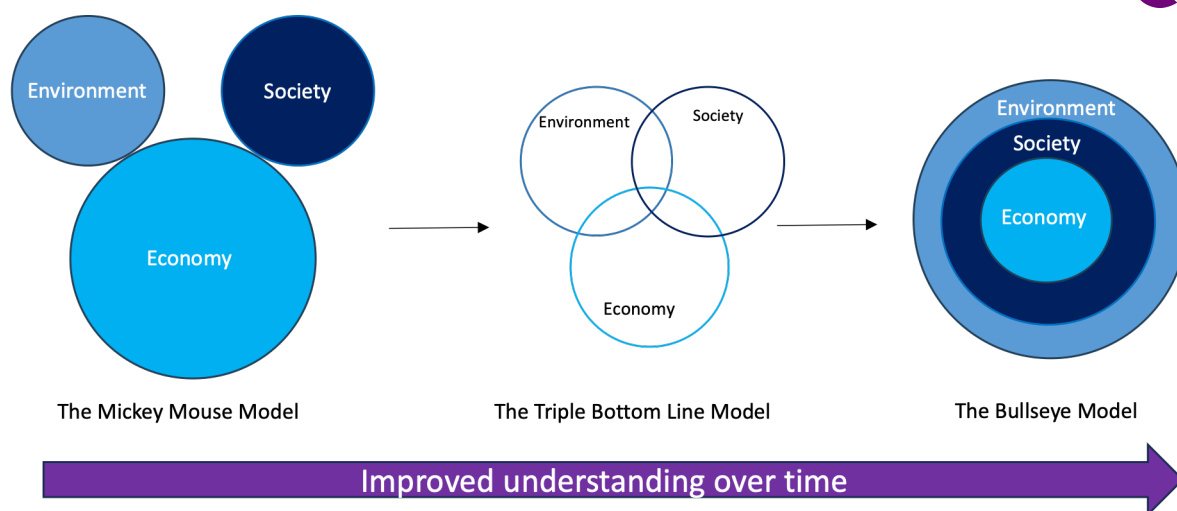


Figure 6 Evolution of economy, society and environment adapted from Darwish (2018)

Environmental sustainability tries to ensure economic and social prosperity while protecting the environment. Environmental sustainability considers the ecology associated with its nearby society. It is also important to ensure that environmental preservation does not lead to the detriment of society or the economy. This is a careful, universal balancing act. Du *et al.* (2013) argue that technology organisations are confronted with profit-driven vs sustainable development approaches. These trade-offs exist in every other sector and therefore add further complexity to environmental sustainability challenges. One of the crucial aspects of sustainability is to be mindful of social and greenwashing. Social washing refers to deceptive advertising strategies on socially responsible products (Rizzi *et al.*, 2020), whereas greenwashing is seen as the promotion of environmentally friendly activities to hide environmentally unfriendly practices in an organisation (de Freitas Netto *et al.*, 2020). Nevertheless, sustainability endeavours display ever-increasing urgency.

The major man-made causes of pollution and environmental degradation are population growth, poverty, urbanization and industrialisation (Das, 2020). South Africa is no exception to these issues. Rapid urbanization and increased population growth have led to increased infrastructure demands which further strain the environment (Chirisa, 2008). Despite housing efforts in South Africa, Turok and Borel-Saladin (2014) argue that this is insufficient for a sustainable trajectory. Evidence from Baloch *et al.* (2020) also suggests that increased poverty and inequality negatively impact the environment by means of CO₂ emissions and pollution. Poverty reduces the capacity to use resources sustainably and increases pressures on the environment: more so in developing countries (Das, 2020). To further complicate this, industrialisation processes to eradicate poverty are expected to worsen environmental quality at the expense of much-needed economic growth (Jin *et al.*, 2018).

In supply chain contexts, supplier selection involves a complex set of decisions which has led to numerous scholars exploring the topic. The careful selection of suppliers enforces a more sustainable supply chain that improves environmental performance in organisations (Yildiz & Yayla, 2015).

In South Africa, researchers have also made efforts to address environmental challenges and promote environmental sustainability. Research on socio-technical transitions has explored an integrated framework to manage technology during sustainability transitions (De Kock, 2020), lean and green performance (Machingura *et al.*, 2024a), and a Lean

and Green greenhouse gas reduction framework for the manufacturing industry (Roopa *et al.*, 2020).

Beyond these ecological and demographic drivers, the very definition of a corporate sustainability strategy remains contested. Adolph and Beckmann (2024) synthesise eight competing perspectives into a shared conceptual framework. Their work found that sustainability itself remains a contested strategic construct even before it is operationalised within a specific discipline such as IE.

Despite the accolades the IE profession enjoys, for some time it has been viewed contentiously as a discipline lacking cohesion and demonstrating low-level engineering content, according to Buzacott (1984). Bailey and Barley (2005) also believe that IE has moved away from traditional work studies, work design and organisation-focused work. This research seeks to contest these by exploring an integrated solution approach that is relevant, impactful, and true to the nature of IE, adopting a transdisciplinary approach.

The case of environmental issues is universal. They are systemic, ever-changing and certainly complex to address (Khallaf, 2011). Sauvé *et al.* (2016) define an environmental issue as a component that societies seek to reduce, preserve or improve to protect the environment. There is a myriad of environmental issues in our world. To simplify this research, only certain forms of environmental issues are reported here. These include industrialisation, water and land pollution and biodiversity loss, among other forms of green waste (Darkoh, 2009; Das, 2020).

2.3.1 Industrialisation

The major man-made causes of pollution and environmental degradation are population growth, poverty, urbanisation and industrialisation (Das, 2020). South Africa is no exception to these issues. Rapid urbanisation and increased population growth have led to increased infrastructure demands, which further strain the environment (Chirisa, 2008). Despite housing efforts in South Africa, Turok and Borel-Saladin (2014) argue that this is not enough for a sustainable trajectory. Evidence from Baloch *et al.* (2020) also suggests that increased poverty and inequality negatively impact the environment by means of CO₂ emissions and pollution. Poverty reduces the capacity to use resources sustainably and increases pressures on the environment more so in developing countries (Das, 2020). A further complication is that industrialisation processes to eradicate poverty are anticipated to worsen environmental quality at the expense of economic growth (Jin *et al.*, 2018). According to Zokaei *et al.* (2017), eight green wastes are recognised. These are formalised in Table 2.

Table 2 Green wastes from Zokaei *et al.* (2017) with context

Green waste	Context
Water usage	Water consumption rates for auxiliary and direct raw material usage
Lost human potential	Lost creativity, human intellect or insight
Physical waste	Scraps, rework, volatile organic compounds (VOCs) or any material derived from processes
Air emissions	Any form of emissions resulting from processes

Green waste	Context
Land contamination	Material or chemical waste entering landfills
Energy consumption	Electricity use throughout any stage in the process
Water dischargers	Non-intended water (contaminated or pure) exiting production systems
Noise and nuisance	Noise pollution owed to production or service processes

This conflicting relationship between industrial growth and environmental quality is not confined to South Africa. Using panel quantile autoregressive distributed lag modelling across major industrialised economies, Onwe *et al.* (2024) confirm that industrial output and urbanisation significantly deteriorate environmental quality by increasing CO₂ emissions, and that this effect is substantially mitigated when energy efficiency is integrated alongside industrialisation and urbanisation. This suggests that industrialisation need not always be viewed antagonistic to environmental sustainability, provided efficiency-oriented interventions are deliberately embedded. Irrespective of the type of waste or viewpoint, the intent is to have this reduced substantially. Various forms of problem solving techniques are used to reduce several green wastes (Fercoq *et al.*, 2016). To structure the approach, the environmental sustainability paradigm needs to be adopted.

2.3.2 Environmental performance

The pursuit of environmental performance has become a focus in various operations to meet regulations and ecological requirements, primarily in manufacturing contexts (Garza-Reyes, 2015). Anthropogenic activities and the repercussions they have on the environment and societies at large have gained growing interest.

More recent evidence extends this pursuit of environmental performance into governance considerations. Essuman *et al.* (2026) demonstrate, in an emerging-economy manufacturing context, that green supply chain management, green innovation and sustainable dynamic capabilities each contribute to corporate environmental performance. Furthermore, this relationship is strengthened by governance quality. This indicates that environmental performance gains are not purely operational but are moderated by the surrounding governance architecture within which an organisation operates.

Farias *et al.* (2019) document various green practices that can be used to ensure environmental performance. Some of these practices are as follows:

- a) Environmental Management Systems (EMS)
- b) Life Cycle Assessment (LCA)
- c) Reduce, Reuse, Recycle (3R)
- d) Design for the Environment (DFE)
- e) Environmental Emission Control (EEC)

EMS enables management to better understand, monitor and improve environmental performance within their organisation by including human resource factors (Daily & Huang, 2001).

2.3.3 Sustainable Development Goals (SDGs)

As part of the UN 2030 Agenda for a sustainable world, the 17 goals speak to social, environmental and economic pillars (Hák *et al.*, 2018). The three year consultation process sought to address the shortcomings of the Millennium Development Goals — the MDGs (Fukuda-Parr, 2016). A core realisation is that societies are required to grow and respond faster than before, given the rising rate of change (Kostoska & Kocarev, 2019). The takeaway is rather simple: to have individuals, communities, enterprises and government more sustainable for the future (Roopa, 2023).

The financial materiality of SDG engagement has also been empirically tested. Lin *et al.* (2025) show that stakeholder engagement plays a pivotal moderating role between SDG-oriented strategies and corporate financial performance, with firms combining comprehensive SDG strategies and high stakeholder engagement to achieve superior financial outcomes. This lends empirical weight to the argument that SDG alignment, when genuinely integrated rather than superficially reported, can be commercially as well as socially advantageous.

While this is of immense value to environmental sustainability, Swain (2018) argues that developing countries are better off focusing on the economic and social policies before the environment. Research also suggests that the environmental SDGs achieve socio-economic development with little association with biodiversity conservation (Zeng *et al.*, 2020).

According to Bose (2020), the Global Reporting Initiative (GRI), the UN Global Compact, and the World Business Council for Sustainable Development created a five-step approach to align business strategies with SDGs. This involves understanding the SDGs, defining priorities, setting goals, integrating and finally reporting and communicating them (GRI, 2015).

However, the transition to circular business models is not without obstacles in developing-country contexts. Ndoka *et al.* (2025) systematically reviewed 107 studies on circular business models in developing economies and identified financial constraints, regulatory and institutional gaps, technological limitations and cultural resistance as recurring barriers, while policy support, innovation and stakeholder engagement emerged as the principal enablers. This reinforces the relevance of a transdisciplinary, stakeholder-inclusive approach when pursuing CE-based competitiveness in a developing-country setting such as South Africa.

2.3.4 Circular Economy

Circular Economy (CE) was pioneered by British economists and first defined as an economic development model of resource recycling (Pearce & Turner, 1989; Wang *et al.*, 2024). The history reported by Wang *et al.* (2024) details its first implementation in Germany's 1996 Waste Management Act with 3R principles (Reduce, Reuse, Recycle) and was later succeeded by 6R which included Redesign, Remanufacture and Recover (Jawahir & Bradley, 2016).

CE has boasted various improvements across many sectors that include international trade, food production, healthcare policy analysis and digitalising the furniture industry (de Lange, 2024; Moustabchir *et al.*, 2024; Nath *et al.*, 2025; Wulf *et al.*, 2024).

The competitive aspect of CE is that it enhances competitiveness through resource efficiency (Garcia-Muiña *et al.*, 2018). In a study by Bag *et al.* (2023), a digital supply chain incorporated CE practice to improve supply chain practice in South Africa. Globally, multinational corporations have found success adopting CE as a competitive tool (Brondoni, 2020). Some drawbacks of CE highlighted by Corvellec *et al.* (2022), are that it is often phrased as something different, neglects established knowledge, and possesses unclear implementation factors and contributions to environmental and social sustainability. Nevertheless, CE is also perceived as a form of green innovation.

The interaction between CE and other emergent paradigms is increasingly being tested empirically rather than assumed. Mora-Contreras and Carrillo-Hermosilla (2025) surveyed manufacturing companies to examine how circular economy practices, eco-innovation and Industry 4.0 jointly relate to sustainability performance and competitive advantage, finding that circular economy adoption is positively associated with both outcomes, particularly when reinforced by digital, Industry 4.0-enabled capabilities. This suggests that CE delivers a stronger competitive dividend when pursued alongside digital transformation rather than as an isolated operational initiative, a consideration directly relevant to how South African manufacturers might sequence their own sustainability investments or decisions.

2.3.5 Green innovation

Green innovation refers to environmentally friendly innovations aimed at reducing environmental impacts while promoting sustainable development. It encompasses new or improved products, processes, or practices that contribute to environmental conservation. The definitions vary but commonly include product, process, and organisational changes designed to support sustainability and reduce emissions (Zhou *et al.*, 2020; Chen *et al.*, 2025). Studies demonstrate that green innovation significantly reduces carbon emissions and environmental degradation. For example, green technological innovations enhance energy efficiency, cleaner production, and eco-friendly practices across industries such as transportation and energy (Chen *et al.*, 2025; Gupta and Sharma, 2023). Policies promoting green innovation in developing countries like China have shown measurable reductions in CO₂ emissions alongside economic benefits (Chen *et al.*, 2025). There is evidence of a positive effect of green innovation on firm performance, although contextual factors such as location and market sensitivity play roles. While some research points to improved financial outcomes from green innovation adoption, other studies note mixed results depending on cost sensitivity and economic context (Zhou *et al.*, 2020; Gupta and Sharma, 2023).

A recent meta-analysis lends further empirical weight to these claims. Fengyu *et al.* (2026) synthesised 48 empirical studies published between 2012 and 2025 and found small to moderate positive associations between green innovation and environmental, financial and innovation performance. A discernible synergy premium features when green product and green process innovations are pursued in combination and not in isolation. This suggests that fragmented, single-dimension green innovation efforts may under-deliver relative to an integrated approach.

Green innovation also applies to supply chains and the circular economy, focusing on renewable energy, waste reduction, and reuse, supported by data analytics. Region-

specific studies, for example, in South African contexts, emphasise the alignment of green innovation strategies with circular economy approaches for improved sustainability outcomes (Hassim, 2021). Methodological Approaches Systematic literature reviews in this field often follow protocols like PRISMA and use bibliometric tools such as Biblioshiny and VOS viewer to analyse trends and map knowledge domains regarding green innovation (Zhou *et al.*, 2020; Zhang and Li, 2024). Recent scholarship highlights the integration of green innovation with renewable energy policies and calls for context-specific approaches in design and implementation to maximise sustainability benefits (Wang *et al.*, 2025; Smith and Jones, 2023).

The financial payoff of green process innovation specifically, as distinct from green products, has also been isolated empirically. Appiah *et al.* (2025) show, using data from small and medium-sized enterprises in a developing country, that green process innovation improves financial performance. In addition, it also suggests that this relationship is strengthened where firms practise resource orchestration, that is, the deliberate structuring, bundling and leveraging of resources. This underscores that green process innovation alone is insufficient; its financial benefits are contingent on complementary managerial capability.

2.4 Forms of knowledge

2.4.1 Transdisciplinary knowledge

The systematic behaviour is demonstrated by a strong research orientation grounded in expanded principles (Belcher *et al.*, 2016), and a holistic consideration of various stakeholders in the research.

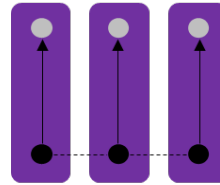
IE is argued to be multidisciplinary (Jovanovic, 2013). This is owing to the vast knowledge areas consulted when solving complex engineering problems. Lately, there has been an increased appreciation and deepened understanding of transdisciplinary research. The development of this form of research is a product of what its antecedents are to be: namely disciplinary, multidisciplinary and interdisciplinary research. Figure 9 demonstrates the varied goal-oriented intent, cooperation and level of integration between disciplines, non-academic and academic bodies of knowledge.

The discipline is first siloed, with limited association between knowledge exchange and theory development; whereas transdisciplinary research has a single goal driven by high integration between disciplines comprising academics and non-academics under varied bodies of knowledge. Dalton *et al.* (2021) believe that in collaborative research that forms part of a multidisciplinary system, individual researchers provide concise but fragmentary solutions embedded within loosely designed and dynamic meta-problem superstructures. A year later, the same researchers explored interdisciplinary research. The researchers forge this as a system comprising researchers assembled through false formation and morphing into a central organising principle that combines intention by unifying aims and methodologies (Dalton *et al.*, 2022).

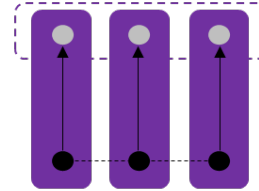
In line with work from Darian-Smith and McCarty (2016) and the International Center for Transdisciplinary Research (CIRET), our understanding of problem difficulties and research approaches can be visualised using Figure 7.

Disciplinary

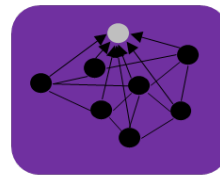
- Within one academic discipline
- Disciplinary goal setting
- Siloed between disciplines
- Development of new disciplinary knowledge and theory

**Multidisciplinary**

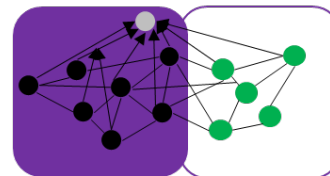
- Multiple disciplines
- Multi-disciplinary goal setting
- Loose cooperation of disciplines during knowledge exchange
- Disciplinary theory development

**Interdisciplinarity**

- Crosses disciplinary boundaries
- Common goal setting
- Integration of disciplines
- Development of integrated knowledge and theory

**Transdisciplinarity**

- Crosses disciplinary and scientific/academic boundaries
- Common goal setting
- Integration of disciplines and non-academics
- Development of integrated knowledge and theory among science and society

**Legend**

- Discipline 
- Non-academics 
- Goal of a research project 
- Movement towards goal 
- Cooperation 
- Integration 

- Thematic umbrella 
- Academic knowledge body 
- Non-academic knowledge body 

Figure 7 Transdisciplinary, interdisciplinary, multidisciplinary and disciplinary overview redrawn from Tress *et al.* (2005) and reproduced with permission from Roopa *et al.* (2024)

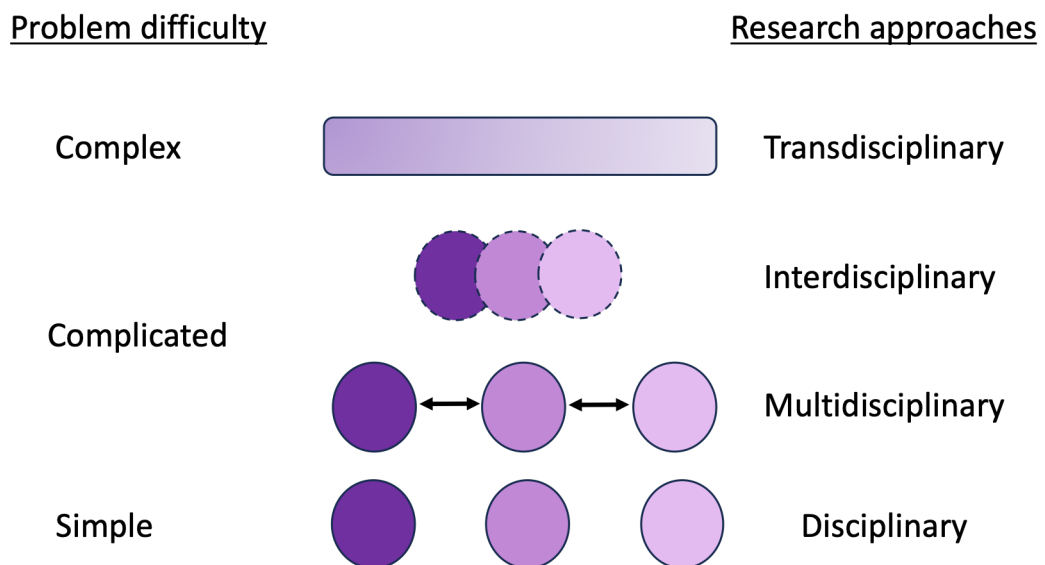


Figure 8 Transdisciplinary as outlined by Darian-Smith and McCarty (2016)

Figure 8 argues that simple research approaches can be solved with disciplinary research strategies. This is especially important in instances where solutions require quick solutions that are clear and require urgent attention in an organisation or industry for acute problems (Mishra *et al.*, 2014). The next classification looks at complicated problems which then rely on multidisciplinary and interdisciplinary research approaches. This type of research rallies a wider range of knowledge areas, which start to overlap or require more specialised understanding (Dalton *et al.*, 2021, 2022). Finally, there is the classification of complex problems which are systemic, ever-changing and volatile. The model above recommends transdisciplinary research as the best resolution although this is not always possible (Darian-Smith & McCarty, 2016).

Some drawbacks to TD research are its fragility in certain contexts (Milberg Muñiz *et al.*, 2025). This is especially challenging in legal research as voiced by Kroeze (2013). Another pressing matter is that although it encourages high stakeholder engagement, it can create misalignment amongst complex methodological integration and time requirements (Axelsson *et al.*, 2020).

In lieu of some of these shortcomings, transdisciplinary knowledge can better address environmental sustainability research. Research has become mindful of the power that transdisciplinarity has in environmental sustainability research. In fact, a particular study by Sakao and Brambila-Macias (2018) suggests that environmental sustainability research can be regarded as a form of transdisciplinary research. Figure 9 makes an effort to map the knowledge application and the interplay concerning multi-, inter- and transdisciplinary research.

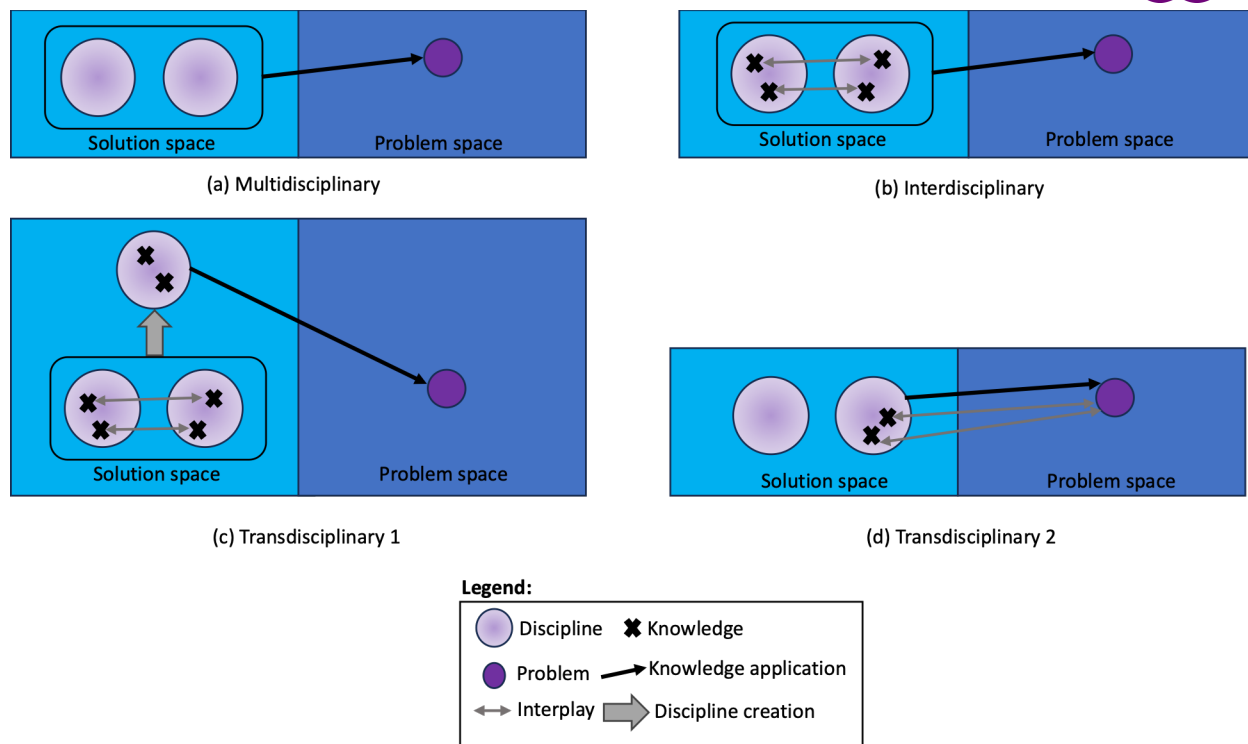


Figure 9 Differences in research types redrawn from Sakao and Brambila-Macias (2018), inspired by Cronin (2008)

As can be inferred from the figure, multidisciplinary research uses one or more disciplines to solve a problem. Interdisciplinary research relies on interactions between specialised forms of knowledge that are combined or sequentially applied to solve said problem. Furthermore, Figure 9 indicates that there are two forms of transdisciplinary research. Transdisciplinary 1 uses a systemic view that develops a general or more common body of knowledge that can perpetuate the formation of a new discipline when solving a problem (Sakao & Brambila-Macias, 2018). In a varying approach, Transdisciplinary 2 targets a siloed yet diverse discipline, with iterated or overlaid problem space interaction during the knowledge application process. However, in some instances, new forms of decision-making and knowledge production summon interaction between academic and non-academic partners that momentarily collaborate to produce comprehensive frameworks (Sakao & Brambila-Macias, 2018).

Phases of TD production entail phases where research is formulated, generated and evaluated (Polk, 2015; Wada *et al.*, 2020). The core activities anticipated in TD co-production processes are outlined in Table 3.

Table 3: Central parts of TD co-production processes reproduced from Polk (2015)

Formulate: Joint problem formulation and project design	
(a)	Initiation: generating and collecting project ideas that assimilate the needs
(b)	Revise and revisit: co-evolution of understanding from involved actor groups
Generate: Co-generation of knowledge and solutions	
(a)	Information collection: joint design and collection of information and data

(b)	Joint analysis and production of results: balancing analytical requirements and skills with situated knowledge and know-how to create joint analysis
(c)	Implementation and communication: application in policy and practice
Evaluate: Formative evaluation of process and impacts	
(a)	Process: on-going reflection on inclusion, collaboration and integration of priorities, expertise, experiences and knowledge from practice and research contexts
(b)	Impact: assessment and reflection upon the usability and transformative capacity of outputs and outcomes

Even though much of the TD research has shown immense success in sustainability research (Angelstam *et al.*, 2013), the TD co-production is confronted with several methodological and practical issues at specific focal areas associated with certain phases of the research, described in Table 4.

Table 4: TD co-production challenges reproduced from Polk (2015)

TD co-production challenges	Methodological issues	Practical issues	Focal areas	Research phases
Capturing multiple framings	What are the roles of contextual values and situated knowledge in co-production? How can they be incorporated into research?	Identify relevant actors, create mutual responsibility, and commitment to develop shared purpose and joint inquiry	Inclusion Collaboration Integration Reflexivity Usability	Formulate: Joint problem formulation and project design
Integrating knowledge diversity	Who has the authority to claim relevant knowledge in co-production? What are the scientific and practical criteria for knowledge integration in co-production?	Create shared knowledge, common understandings and shared frames of reference, promote group processes and reflexivity	Inclusion Collaboration Integration Reflexivity Usability	Generate: Co-generation of data, joint analysis and implementation
Contributing to societal change	How are reliable knowledge and social robustness created, implemented and	Managing organisational and cognitive mismatches, lack of time,	Inclusion Collaboration Integration	Evaluate: Formative evaluations of

TD co-production challenges	Methodological issues	Practical issues	Focal areas	Research phases
	assessed in co-production processes?	scalability, generalizability	Reflexivity Usability	processes and impacts

Broader trends in the sustainability science literature corroborate these trends in for TD's problem-solving capacity. Brandt *et al.* (2013), in a widely cited review of transdisciplinary research in sustainability science, observe that although the field has matured considerably, empirical studies rarely operationalise TD principles within a single, engineering-grounded artefact, a gap this research aims to address.

One can gauge that there is a high level of collaboration, and hence integration, that must exist to ensure that transdisciplinary research is a success. Figure 10 demonstrates the degree of interaction and integration between academic and non-academic participants based on the type of research shadowed.

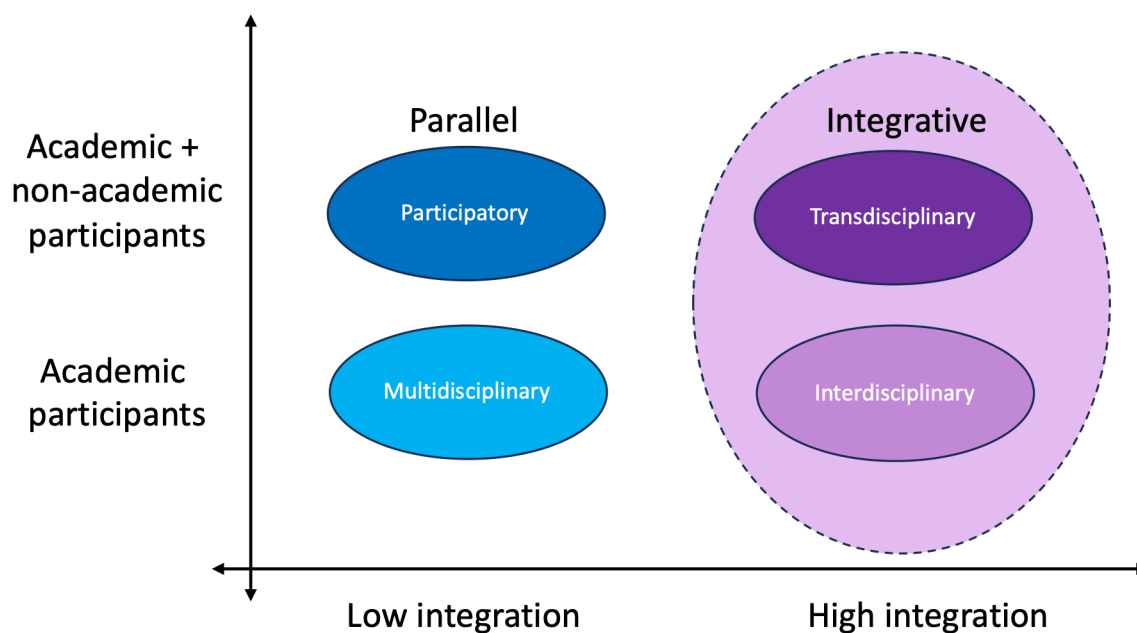


Figure 10 Integration degree and stakeholder involvement approach redrawn from Sakao and Brambila-Macias (2018)

Low levels of integration exist within research projects which function in parallel, and these are seen as participatory or multidisciplinary. Non-academic participants become more involved when pursuing participatory or transdisciplinary research. It also becomes apparent that interdisciplinary and transdisciplinary research is centred around high integration among various stakeholders.

Beyond describing what transdisciplinary research is, recent work has turned to the practical question of what those conducting it are actually expected to do. Hofmann *et al.* (2025) propose a reflection tool that articulates the diverse roles researchers adopt within inter- and transdisciplinary sustainability research. This could range from knowledge broker to reflective scientist, arguing that explicitly naming these roles improves the

quality and accountability of TD collaboration. This role-based perspective complements the process-oriented view of TD co-production discussed by clarifying who is responsible for enacting each phase.

The creation of these forms of knowledge can be further classified as tacit or explicit in nature, as further explained in the succeeding subsection.

2.4.2 Tacit and Explicit knowledge

Knowledge has, for many centuries, been cherished and perpetuated across civilisations. Knowledge can be classified as tacit or explicit knowledge. Tacit knowledge is a form of implicit knowledge used for formal learning in traditional academic subjects and instances of pragmatic investigations during the transmission of skills and expertise (Gascoigne & Thornton, 2014). This form of knowledge is practical, action-orientated and can stem from personal experience (Smith, 2001). Tacit knowledge can be further classified into the following types (Collins, 2019):

- Relational tacit knowledge – principles that possess rich descriptions
- Somantic tacit knowledge – events possible with limited, poor or no possible description
- Collective tacit knowledge – collective wisdom and knowledge from society

In contrast, explicit knowledge is more concerned with academic knowledge in formal language with more technical data or information that is readily communicated, and requires a level of academic knowledge or understanding with predictable acts of acquisition in stable environments (Smith, 2001).

The generation of this knowledge is eloquently described and visualised by Nonaka and Nishiguchi (2001). A representation of this has been reproduced in Figure 11.

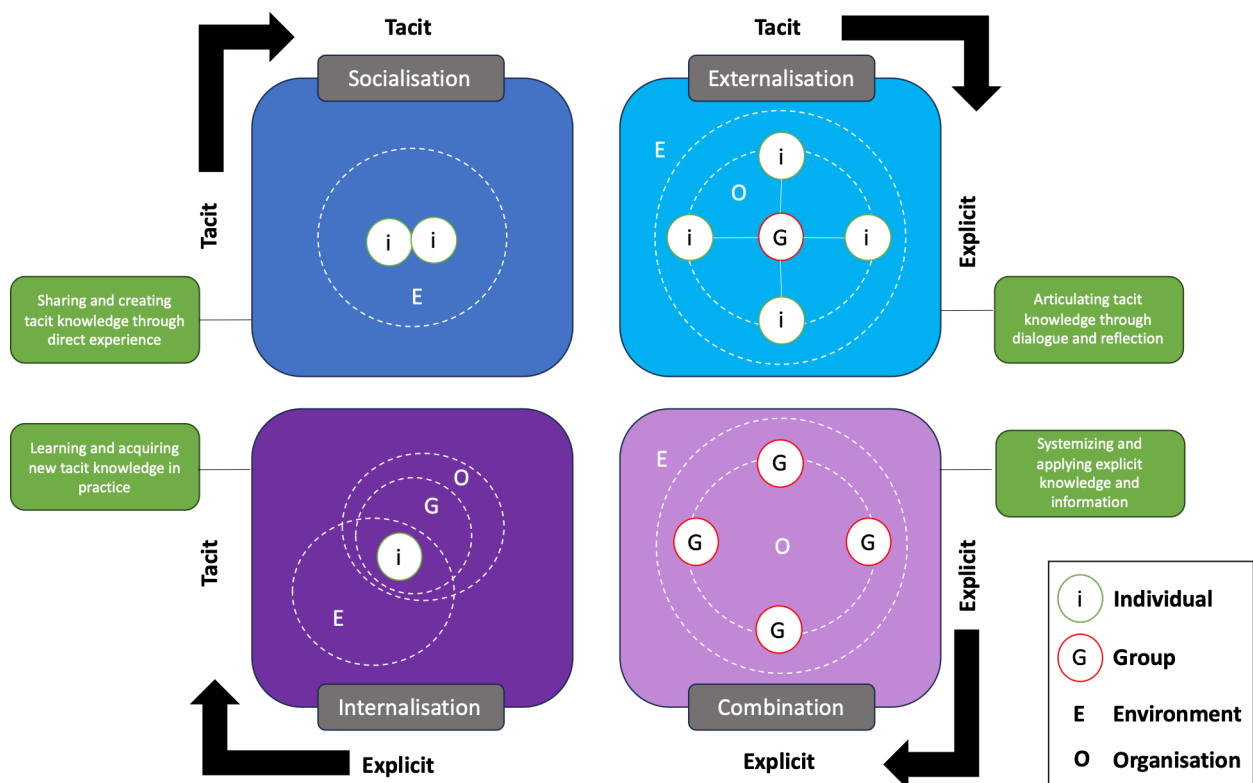


Figure 11 Knowledge Generation SECI model from Nonaka and Nishiguchi (2001)

The socialisation exchanges tacit knowledge between individuals, while externalisation sees the conversion of implicit, to explicit knowledge. The combination domain converges explicit knowledge in a complex fashion. The internalisation segment welcomes learning and the acquisition of new knowledge between various groups, the individual and the environment. The creation and evolution of knowledge can be unpacked into a life cycle and spiral model.

The transfer of tacit knowledge specifically, as opposed to its mere conversion into explicit form, has also received recent empirical focus. Shahzad and Soroya (2025) apply a structural equation modelling approach to test a tacit knowledge transfer model in an academic context and confirm that the capturing, sharing and application stages of tacit knowledge transfer are each significant, sequential predictors of successful knowledge transfer outcomes. This empirical validation of a staged transfer process reinforces the practical relevance of the tacit-to-explicit conversion mechanisms beyond the purely theoretical SECI formulation.

2.4.3 Knowledge life cycle and spiral model

Nonaka (2009) is known to have popularised the discussion on tacit and explicit knowledge. Explicit knowledge is the more tangible knowledge product in the form of documentation and is easier to formalise, whereas tacit knowledge is presented as the more subconscious knowledge that involves intuition (Nonaka & Takeuchi, 2007). Figure 12 demonstrates the interrelation between tacit and explicit knowledge over time.

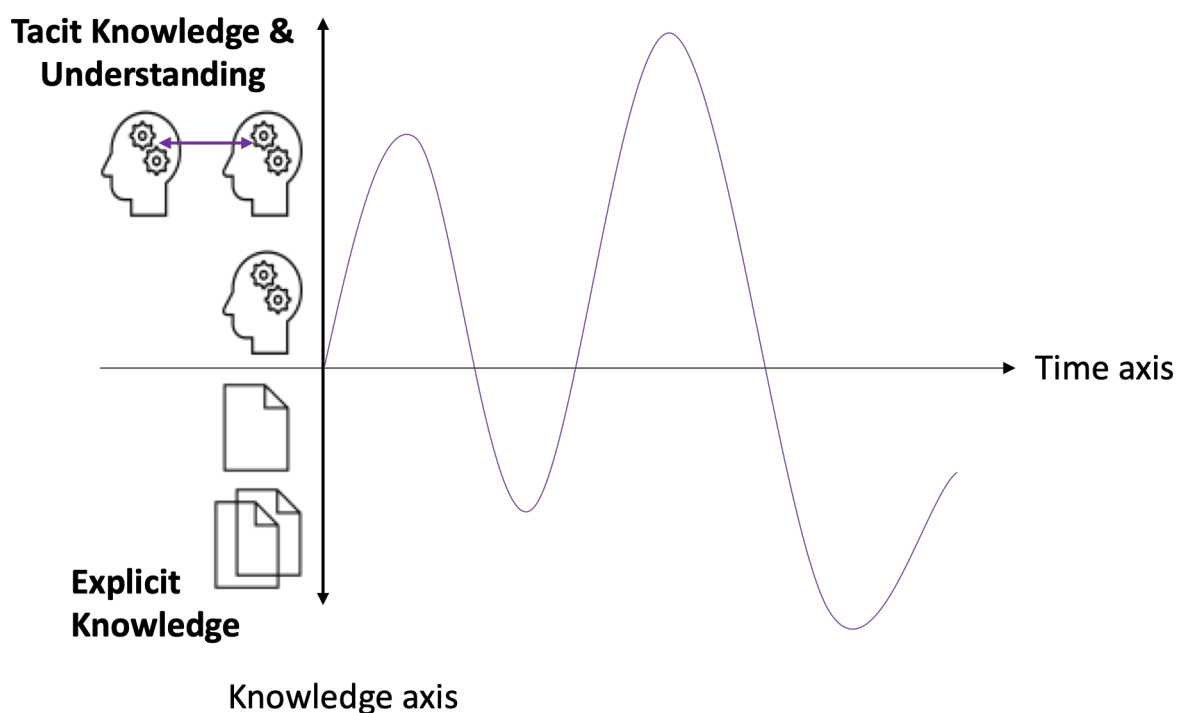


Figure 12 Interrelated knowledge life cycle redrawn from Nonaka and Takeuchi (1995)

According to this diagram, the transfer of knowledge between these forms of knowledge fluctuates over time as the knowledge span of the individual progressively increases. Another intriguing representation of knowledge is the knowledge spiral, as depicted in Figure 13.

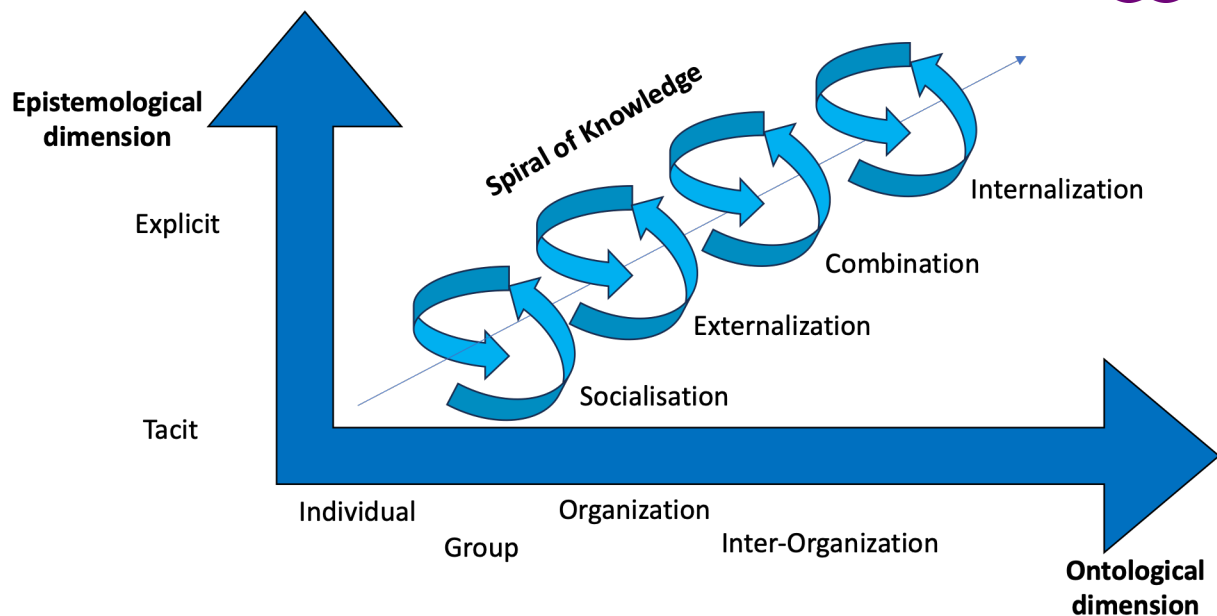


Figure 13 Knowledge work processes as knowledge spiral redrawn from Seufert *et al.* (2004)

The knowledge spiral transcends across various levels in a transformation process involving explicit and tacit knowledge creation. The nature of the spiral also resonates with the work of the SECIA model previously presented. The spiral illustration showcases knowledge network potential which an organisation can design and incorporate into their operations.

The practical value of managing this knowledge life cycle intentionally, is borne out by recent empirical work. Cristache *et al.* (2025) demonstrate that knowledge management, when treated as an integrated set of creation, integration, implementation and sharing processes rather than as isolated activities, exerts a measurable positive influence on both innovation and organisational performance. This lends empirical support to the view that the knowledge spiral is not merely a descriptive heuristic but a process organisations can actively manage to convert tacit engineering and sustainability knowledge for a durable performance advantage within an organisation.

2.4.4 Knowledge supply chain

This research seeks to create transdisciplinary knowledge by drawing on multidisciplinary domains within IE and environmental sustainability. One way to understand the implications of cultivated knowledge is to examine its supply chain. Figure 14 illustrates the knowledge supply chain from Du Preez and Louw (2007), which shows various stakeholders within an integrated knowledge network.

The migration and evolution of knowledge ripples across public, private and user domains with various stakeholders. It is because of this same illustration that special focus will be placed on the competitive stage of the model, which is aligned to private domains. This involves the identification, collection and application of knowledge that harmonises with the three business execution levels.

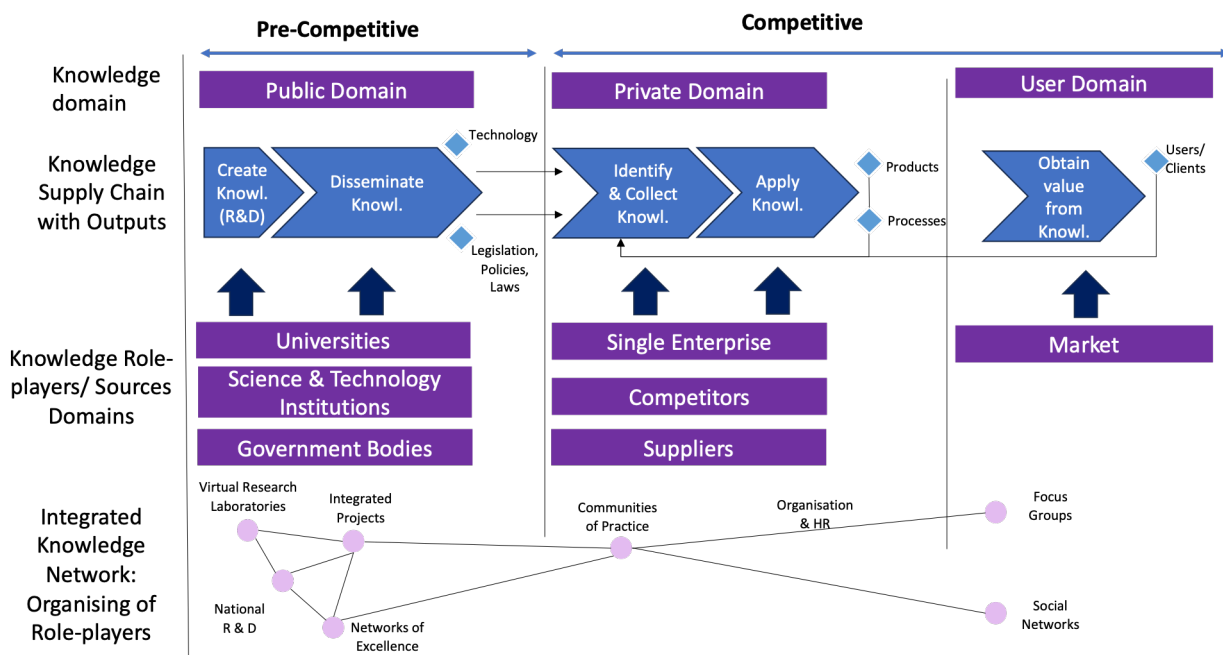


Figure 14 The Knowledge Supply Chain redrawn from Du Preez and Louw (2007)

The knowledge supply chain concept itself continues to be refined through systematic review. Mohsin *et al.* (2025) conducted a systematic review and bibliometric analysis of sustainable supply chain management research and found that the field has evolved from a narrow operational focus toward one that explicitly incorporates knowledge management, digitalisation and sustainability considerations as co-equal concerns. This evolution reinforces the appropriateness of treating knowledge, alongside materials and information, as a distinct flow within this supply chain model.

The consideration of academics (universities) and managers and practitioners (private domain) in this research helps motivate the configuration and pre-competitive and competitive traits that collectively identify, create, collect, apply and disseminate knowledge, which represents a complex network of stakeholders. This further demonstrates the transdisciplinary nature of this study. Bibliometric evidence confirms the continued expansion of this research area. A bibliometric study from Khanmirzaee *et al.* (2025) was able to chart the growing intersection between supply chain management and knowledge management research, underscoring that knowledge supply chains are an active and expanding scholarly domain rather than a static, fully resolved concept.

2.4.5 Theory, principles and practice

A core focus for this research is the categorisation of the various knowledge components as strategies, theories, methods and practices. A similar categorisation from Schlüter *et al.* (2023) suggests that metaphysical assumptions, concepts, principles, methods and practices aid us in understanding the world and acting on it from two different directions of application. These interactions are encapsulated in Figure 15.

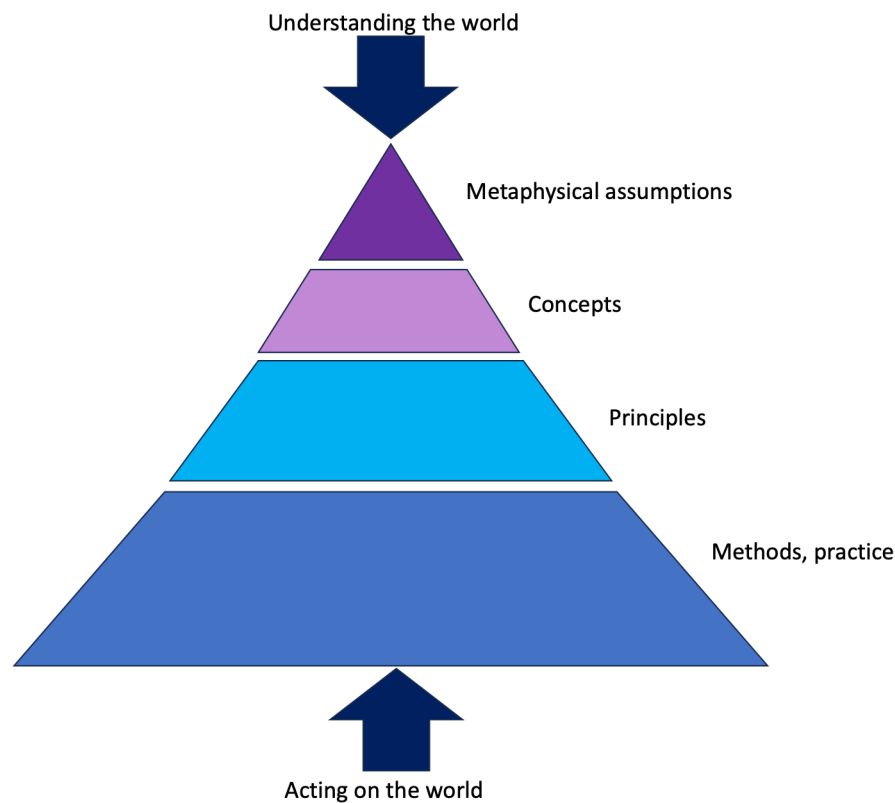


Figure 15 Difference between theory, principles and practice, redrawn from Schlüter *et al.* (2023) and similar to Koskela and Kagioglou (2005)

As explained by Schlüter *et al.* (2023), concepts help us understand the world. Methods and practices help bridge concepts and contextualise them more. Finally, principles are more generic and less contextual. In order to act on the world, the formulation of strategies to remain competitive becomes pertinent.

As a way of acting on the world through strategy formation. The relationship between theoretical abstraction and applied practice remains an unresolved epistemological question in strategic management more broadly. Parkhe (2026) argues that bridging the theory-practice gap requires strategic management to be treated simultaneously as a social science and an applied science, given the differing worldviews of scholars and practitioners. New knowledge can only be co-created through genuine exchange between the two groups. This epistemological stance directly motivates the transdisciplinary, practice-engaged design of this research.

The focus of this research is to investigate the notions of a sustainable competitive advantage for South Africa. In doing so, this research classifies the method of execution along theory, principles and practice as a way of acting on the world through strategy formation.

2.5 Sustainable competitive advantage

Companies are constantly adapting their strategies to remain competitive in their respective industries. Lately, a sustainable competitive advantage is a core dimension to an organisation's strategy, since it is a way of incorporating sustainability practices in their value offering. As indicated by Chikán *et al.* (2022), the term competitiveness was spurred by the work of Porter. One way of gauging competitiveness is through firm (organisational) competitiveness and performance. Organisational competitiveness

establishes the capability of the firm to meet customer demand at a profit and is achieved by adapting to social and economic conditions (Chikán, 2008). It is based on profitability, growth, market value, the total return to shareholders, economic value added and customer satisfaction (Charles & Ochieng, 2023).

Supply chain management is inherently a part of IE. This sub-discipline explores ways of managing the range of activities that render products and services between suppliers and customers (Jacobs & Chase, 2018). According to Gonyora *et al.* (2021), competitiveness drivers in supply chain management are reliant on resource-based view, absorptive capacity and dynamic capability as theories, all of which underpin efforts to maintain a competitive advantage using open innovation.

The competitive theory from Porter states that there are two parts for competitive advantage, namely cost leadership and differentiation (Tanwar, 2013). The following source of literature has configured a leaders and laggards framework on sustainability and operational practices with Figure 16. This taxonomy explains the sustainable and operational practices according to Cartesian segmentation of leaders and laggards belonging to each domain.

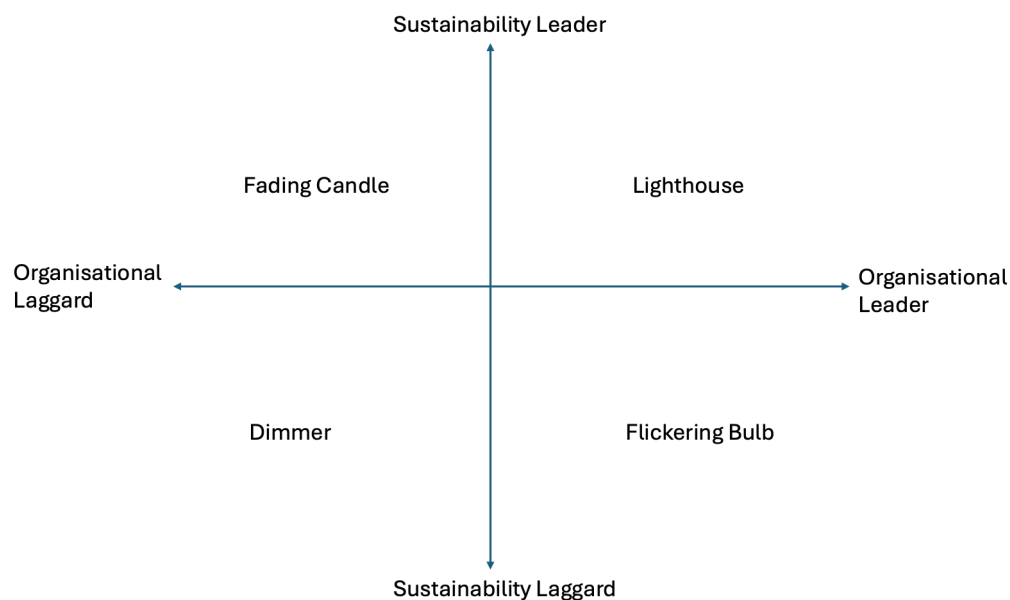


Figure 16 Sustainability and Organisational Leaders vs. Laggards Framework redrawn from ISS Insights (2026)

The model from ISS Insights (2026) argues that sustainability presents the opportunity to create a competitive advantage. It suggests that sustainability has evolved from a compliance-driven risk mitigation tool into a core strategic driver of long-term competitive advantage and operational excellence. By integrating environmental, social, and governance (ESG) metrics with operational efficiency, the high-sustainability firms are believed to foster innovation and resource efficiency, leading to superior financial resilience and market valuation. Ultimately, their research posits that companies embedding ESG into their business models are better positioned to navigate transition risks and attract capital, outperforming 'operational laggards' by prioritising long-term value creation over short-term gains.

One recently developed SCA taxonomy is that of Sołoducho-Pelc and Sulich (2020), visualised in Figure 17. Innovations ensure a competitive dynamic in an organisation to either maintain or surpass its current standings (Veselica Celić, 2025). In the same

breath, should an innovation materialise incorrectly, they can also lose their advantage in an existing market by failing to adapt to dominant designs or technological discontinuities.

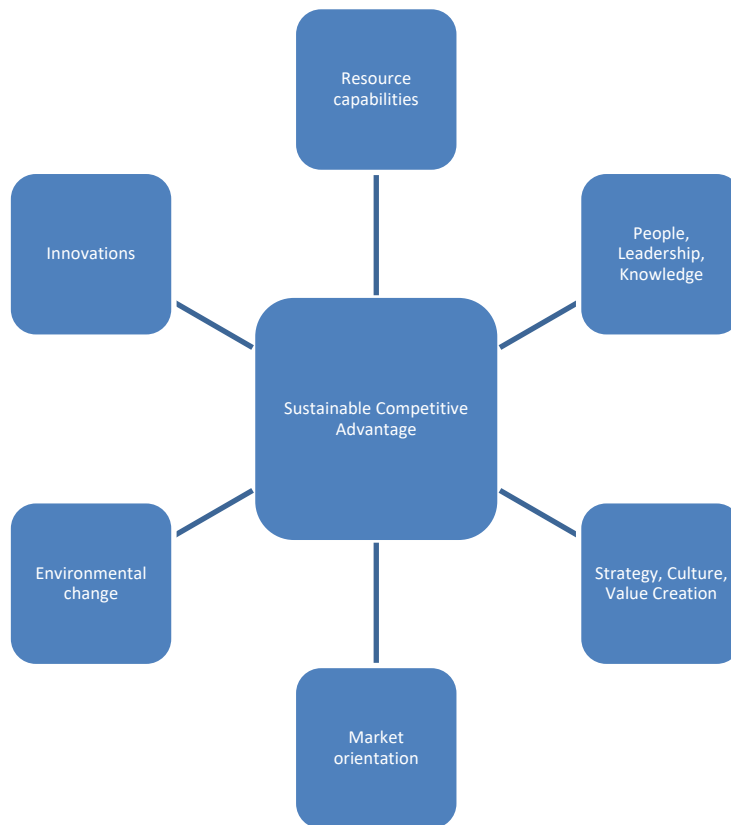


Figure 17 Sustainable Competitive Advantage Factors redrawn from Sołoducho-Pelc and Sulich (2020)

Sustainable competitive advantage (SCA) remains a central concept in strategic management. The Resource-based View proposed by Barney (1991) and the dynamic capabilities framework by Teece *et al.* (1997) emphasise the importance of unique and adaptable organisational capabilities. The Natural Resource-Based View (NRBV) introduced by Hart (1995) explicitly links environmental sustainability to competitive advantage. However, scholars such as McGrath (2013) argue that competitive advantages are increasingly transient.

2.5.1 Resource-Based View (RBV)

The Resource-Based View (RBV) has established itself as a foundational theoretical framework in strategic management, fundamentally shifting the analytical focus from external industry structures to the internal attributes of the organisation. Originally conceptualised by Wernerfelt (1984) and significantly advanced by Barney (1991), the RBV posits that a firm is best understood as a unique bundle of resources and capabilities. Rather than seeking market power through external positioning, the RBV argues that sustained competitive advantage is internally generated (Barney, 1991). This advantage is contingent upon the firm's ability to acquire, develop, and deploy resources that meet the stringent criteria of the VRIO framework. The framework dictates that it must be Valuable, Rare, Inimitable, and the organisation must be appropriately structured to exploit them (Barney, 1991; Barney *et al.*, 2021). Consequently, the theory places a premium on intangible assets, namely proprietary knowledge, organisational learning, and embedded operational processes. These are inherently difficult for competitors to replicate or substitute.

A primary advantage of the RBV is its capacity to explain how firms achieve a sustainable competitive advantage even when operating in identical market environments. By emphasising internal heterogeneity, the framework provides researchers and practitioners with a robust mechanism to analyse the strategic co-specialisation of assets (Lubis, 2022). Furthermore, the core tenets of the RBV have proven highly adaptable, allowing it to bridge the gap between traditional strategic management and pressing contemporary challenges. Most notably, the framework was extended by Hart (1995) into the Natural-Resource-Based View (NRBV). This critical evolution argues that a firm's long-term competitive advantage will increasingly depend upon its relationship with the natural environment. By applying the RBV's internal focus to ecological imperatives, researchers can use transdisciplinary approaches to identify how operational efficiencies, such as those optimised in IE systems, can be integrated with environmental sustainability to yield both ecological and economic value (Hart & Dowell, 2011).

The explanatory reach of RBV continues to be tested empirically in novel contexts. Clark *et al.* (2026) apply a holistic resource-based theory framework to nature-based tourism destinations. The study found that the strategic orchestration of place-based resources by destination leaders, rather than resource possession alone, was decisive in generating a sustained competitive advantage. This reinforces the argument, developed further below, that RBV-derived advantage is contingent on organisational action and orchestration and not merely on resource endowment.

Despite its widespread academic application and theoretical malleability, the RBV has faced rigorous critique regarding its epistemological boundaries and practical utility. A predominant disadvantage is the theory's lack of managerial and operational prescription. Critics such as Kraaijenbrink *et al.* (2010) argue that while the RBV effectively describes the characteristics of successful resources being valuable and rare, it offers minimal guidance on the actual processes required to cultivate these resources within complex, real-world systems. Furthermore, the framework has been challenged for treating the concept of value as an exogenous variable. Since RBV relies on external market contexts to determine what makes an internal resource valuable, it risks circular logic and struggles to stand entirely independently of the environmental models it seeks to challenge (El Shafeey & Trott, 2014). In addition, the theory's foundational assumption of resource heterogeneity creates a uniqueness dilemma: if every organisational system is fundamentally idiosyncratic, distinguishing which specific variables are genuinely responsible for performance outcomes becomes an incredibly complex empirical challenge. To address some of its shortcomings, VRIO can be employed more stringently: this is discussed in the following subsection.

2.5.2 VRIO framework

The VRIO framework comprises four distinct criteria associated with Value, Rarity, Inimitability, and Organisation, which serve as the diagnostic heart of the Resource-Based View (RBV). Initially popularised by Jay Barney in the mid-1990s as a refinement of his earlier VRIN model, the framework is designed to move beyond theoretical abstraction by providing a systematic method for evaluating a firm's internal resources (Hesterly & Barney, 2014). By applying these four filters, researchers can determine whether a specific resource or capability acts as a source of competitive parity, temporary competitive advantage, or sustained competitive advantage.

The primary advantage of the VRIO framework is its granular, prescriptive nature. Unlike the broader RBV, which can be criticised for being overly descriptive, VRIO provides a

logical, sequential path for assessing organisational competitiveness (Barney, 1995). For an engineering or management practitioner, this offers a practical diagnostic tool should a resource be valuable but not rare, as it provides only competitive parity. Alternatively, should it be deemed valuable and rare but easily imitated, it yields only a temporary advantage. Only when a resource satisfies all four criteria can a firm successfully capture the economic rent generated by its unique assets (Hesterly & Barney, 2014; Peteraf & Barney, 2003).

Recent large-sample evidence situates DC theory more firmly within a sustainability context. Bhadra *et al.* (2024) drew upon data from 210 large Indian manufacturing firms, demonstrating that a higher-order dynamic sustainability capability facilitates environmental and social performance through managerial capability. However, this relationship is moderated by organisational inertia and environmental turbulence. This confirms that dynamic capabilities can be explicitly oriented toward sustainability outcomes rather than general market responsiveness alone.

Despite its practical utility, the VRIO framework is not without its limitations. A significant critique is its inherent static nature; VRIO often functions as an analysis of one instance, which can fail to account for the dynamic, hyper-competitive environments typical of modern industries. It is argued that in sectors characterised by rapid technological disruption, a resource that is currently "inimitable" may become obsolete, or its value may evaporate, rendering the VRIO assessment temporarily accurate but strategically misleading (Priem & Butler, 2001). Additionally, the Organisation component is frequently criticised as being the most ambiguous part of the framework. While the first three criteria (V, R, I) are relatively easier to measure via market analysis or resource benchmarking, the Organisation criterion assessing internal policies, structures, and culture can be seen as an attempt to appease all.

Furthermore, the framework assumes that firms have a high degree of transparency regarding their own internal operations and the capabilities of their competitors. In practice, assessing whether a resource is truly "inimitable" is highly speculative, as firms often lack the necessary intelligence on rival companies' tacit knowledge or deep organisational routines (Priem & Butler, 2001). Despite these critiques, when applied within a transdisciplinary context to integrating environmental sustainability into engineering processes, VRIO remains a powerful lens for identifying which specific operational practices contribute to a green competitive advantage versus those that are merely operational necessities (Hart & Dowell, 2011).

A recent qualitative case study grounds these criteria in a concrete organisational setting. Amaya *et al.* (2024) applied the VRIO framework to a knowledge-intensive pharmaceutical organisation in an emerging market and found that plant and equipment together with the tacit technical knowledge of its workforce were the resources conferring competitive advantage, principally because of their rarity rather than their value alone. This finding illustrates that VRIO's diagnostic power lies less in identifying valuable resources, which are often plentiful, and more in isolating the rare and organisationally embedded ones.

2.5.3 Dynamic capabilities

While the Resource-Based View (RBV) provides a robust framework for understanding competitive advantage through stable resource bundles, it has often been criticised for its static nature. In response to the increasing volatility of global markets, the Dynamic Capabilities (DC) framework emerged as an essential theoretical extension. Formally

introduced by Teece *et al.* (1997), dynamic capabilities are defined as a firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments. Rather than focusing solely on the possession of resources, this perspective emphasises the process of change, suggesting that long-term survival depends on an organisation's capacity to evolve its resource base in alignment with shifting technological and market landscapes (Teece, 2007).

The framework is generally operationalised through three primary activities: (1) Sensing, (2) Seizing, and (3) Transforming. According to Teece (2007) and Helfat and Peteraf (2015), sensing involves the analytical processes required to identify and shape opportunities through scanning, searching, and interpreting market developments. The next phase, seizing, refers to the mobilization of resources to address those opportunities and capture value through effective business models and decision-making. Finally, transforming welcomes the continuous renewal of organisational structures and assets to ensure that the firm remains relevant.

The primary advantage of the DC framework is its high degree of relevance for fast-moving industries where the useful life of a resource is short-lived. By focusing on organisational agility and learning, the DC view explains why some firms can consistently innovate and survive industrial disruptions while others fail (Helfat & Winter, 2011). Furthermore, this perspective is particularly valuable for transdisciplinary research involving complex systems. In the context of engineering and operational management, dynamic capabilities allow for the strategic integration of new environmental technologies or digital transformation tools into existing workflows, ensuring that a balance between operations and sustainability is maintained even as external regulations or technologies shift (Teece, 2007).

Evidence from other developing economies illustrates that mechanisms consistent with both NRBV and Dynamic Capabilities can coexist empirically. Masud *et al.* (2026) show that in Bangladesh, digital leadership, human capital and knowledge management, capabilities more consistent with a Dynamic Capabilities perspective, drive a sustainable competitive advantage largely through eco-innovation, moderated by green marketing. This suggests that in some developing-country contexts, DC- and NRBV-aligned mechanisms may operate in tandem rather than in opposition.

Despite its popularity, the DC framework has been criticized for the lack of a clear boundary between a 'resource' and a 'capability, leading to potential tautology: an instance where a firm is said to have dynamic capabilities because it is successful, and it is successful because it has dynamic capabilities (Kraaijenbrink *et al.*, 2010). Additionally, the framework is often seen as being difficult to measure empirically. Since sensing, seizing, and transforming are deeply embedded in an organisation's tacit routines and managerial cognitive processes, they are harder to quantify than tangible resources (Helfat & Peteraf, 2015). There is the risk of capability traps, where an over-emphasis on constant change can lead to organisational exhaustion and a lack of focus, potentially destroying the very efficiencies that a firm's core IE processes were designed to create (Helfat & Winter, 2011). DC is later contrasted with the Natural-Resource-Based View (NRBV) now discussed.

2.5.4 Natural-Resource-Based View (NRBV)

The Natural-Resource-Based View (NRBV) frames firm strategy around three interlinked capabilities: pollution prevention, product stewardship and sustainable development.

These environmental strategies are presented as sources of sustained competitive (economic) advantage. However, an explicit social link is not specified. NRBV is a firm-level theory that integrates environmental constraints into resource-based thinking and positions environmental strategy as a source of competitive advantage. Furthermore, the NRBV centres on firm capabilities in a way that reduces the environmental impact, while simultaneously creating strategic value for the firm (Cahyadi *et al.*, 2022). Despite its advantages, it is argued that the management of the firm's relationship with the biophysical environment calls for strategic resources and capabilities that yield competitive advantage when correctly developed and implemented (Cahyadi *et al.*, 2022). Literature demonstrates that scholars combine NRBV ideas with broader sustainability intent in empirical and applied research.

The NRBV stages entail three core stages which function as a strategic capability. It is worth mentioning that each stage places emphasis on different firm actions and resource commitments which are intrinsically linked to environmental performance and firm value (Hart, 1995). According to Cahyadi *et al.* (2022) the first stage (pollution prevention), focusing on reducing the inputs, emissions and waste by employing cleaner production techniques and process improvements to lower the environmental impact and resource used. The next stage considers product stewardship, which emphasises life-cycle responsibility for product and services such that firms are able to control their downstream impacts and stakeholder interactions across the entire value chain. The last phase seeks to ensure sustainable development by investing in cleaner technologies and business models that decouple growth from environmental degradation and create new market opportunities.

Hart (1995) also compiles evidence from several firms which demonstrates firms can either sequence or accumulate capabilities, and that the parallel or concurrent approach creates progress across multiple stages simultaneously.

2.5.5 Debate between NBRV and Dynamic Capabilities

The debate between the Natural-Resource-Based View (NRBV) and Dynamic Capabilities (DC) often centres on whether an organisation's competitive advantage is derived from its relationship with the external environment or its internal processes for change. While DC focuses on the internal ability to sense, size and transform assets, it is argued to be dismissive of environmental considerations. This is particularly due to its focus on market changes (Harreld *et al.*, 2007). For firms navigating modern climate challenges and regulatory shifts, NRBV outperforms DC by being more contextual. Moreover, one advantage of NRBV is that the physical environment is considered a direct constraint and source of advantage (Hart, 1995). It gives recognition to limited natural resources and degrading ecosystems, which drive long-term viability.

Furthermore, the three interconnected strategies geared towards pollution prevention, product stewardship and sustainable development are embedded in an organisation's culture and external stakeholder relationships. Although DC might become favourable for competitors that adapt their business model, the tacit knowledge within an organisation through NBRV is also advantageous.

While DC achieves incremental or evolutionary gains within existing market structures (Eisenhardt & Martin, 2017), NRBV is designed for discontinuous change (De Stefano *et al.*, 2016). As global economies transition toward circularity and decarbonization, NRBV provides a strategic logic for sustainable development. Fundamentally, DC views ecological dynamics as a cost to be managed instead of a direct avenue for an SCA.

DC theory does not intuitively solve for the rising cost of raw materials or energy volatility (Shuen *et al.*, 2014). In contrast, NRBV prioritises product stewardship by considering the entire product life cycle as a foresight approach that reduces resilience, resources-based approaches that internal agility is unable to cater for (Lewis, 2017; Royer & Simon, 2024). It also reduces the dependency on volatile commodity markets.

Recent scholarship has begun to question whether this debate is a binary choice. Alkaraan *et al.* (2024) show that firms can reinforce their green business strategies by explicitly integrating NRBV and Dynamic Capabilities logic alongside Industry 4.0 and governance mechanisms, finding that the two theoretical lenses function as complements rather than substitutes when firms pursue Industry 4.0-enabled sustainability transitions. This empirical evidence suggests that, in practice, the most resilient organisations draw selectively on both the ecological grounding of NRBV and the adaptive orientation of DC. Given that this research intends to understand the aspects of various organisations, the business-nature interface from NRBV is more relevant than Dynamic Capabilities. Since environmental sustainability is a specific knowledge domain within the scope of the research, the goal of Dynamic Capabilities being adaptive to market change is not as relevant as the ecological limits NRBV considers. Furthermore, NRBV gives focus on the natural environment and hence a closer association with the sustainability narrative this research explores within IE, using a Transdisciplinary knowledge creation process.

2.6 Biomimicry

Nature has been fine-tuning its systems for over three billion years, creating a massive repository of blueprints that humanity is only just beginning to decode. Biomimicry, derived from the Greek words *bios* and *mimesis*, represents a scientific and design discipline that looks toward these biological successes to find sustainable solutions for complex human challenges. As Benyus (1997) famously articulated in her seminal work, this approach shifts our perspective of the natural world from a warehouse of resources to be extracted into a model, measure, and mentor to be emulated. By treating nature as a model, designers can imitate biological forms and processes. Using nature as a measure allows for the evaluation of innovations against ecological standards of what works and what lasts. Third, viewing nature as a mentor introduces a new way of valuing the environment not for what we can take from it, but for what we can learn from it.

The current literature surrounding biomimicry suggests a significant paradigm shift from simple efficiency to a deeper regenerative engineering. Early applications of bio-inspired design were often limited to the organism level, where the physical form of a plant or animal was copied for aesthetic or basic aerodynamic purposes. However, recent scholarship by Wang *et al.* (2025) indicates that the field has matured to include behaviour- and ecosystem-level mimicry. This means that instead of just copying the shape of a leaf, modern engineers are looking at how a forest manages its nutrient cycles, or how a swarm of insects coordinates its movements without a central leader. This shift is crucial for the transition from a linear "take-make-waste" economy to a circular economy where waste is essentially non-existent. Furthermore, researchers such as Rahubadda *et al.* (2025) have highlighted that bio-inspired architecture can reduce carbon emissions and operational energy by up to 50%, proving that these models are not just theoretical but practically essential for our planet.

The methodological rigour of biomimetic design has also advanced considerably. Bian *et al.* (2025) propose a systematic evaluation model, using the analytic hierarchy process, for assessing the sustainability credentials of biologically inspired product designs,

moving the field beyond descriptive case studies toward a structured, replicable evaluation methodology. This provides justification for variations to traditional biomimetic or biomimicry designs.

In the realm of IE, biomimicry is being used to tackle the increasing complexity of global supply chains and material science. One of the most compelling recent developments involves the use of swarm intelligence and bio-inspired neural networks to manage logistics. A study published in 2026 introduced the Ch-EGN model, which mimics the communication patterns of biological neurons and the hierarchical processing of the human visual cortex to predict delivery risks (Khaleghi *et al.*, 2026). In traditional IE, a centralised 'brain' often struggles to manage thousands of moving parts simultaneously. By adopting the decentralised, self-organising principles seen in ant colonies or neural pathways, companies can create supply chains that are much more resilient to sudden disruptions. This specific bio-inspired approach achieved nearly 99% accuracy in risk identification, demonstrating that biological systems offer a level of optimisation that traditional human-centric algorithms often lack (Khaleghi *et al.*, 2026).

Beyond digital systems, IE also benefits from the physical properties of biological structures, such as the unique texture of shark skin. Shark skin is covered in microscopic grooves called denticles, which serve two distinct industrial purposes: reducing drag and preventing the buildup of bacteria. As noted in recent reviews of biomimetic materials (Karuppusamy *et al.*, 2026), these micro-textures suppress the formation of turbulent vortices in fluids, which has been applied to the hulls of ships and the wings of aircraft to significantly improve fuel efficiency. Perhaps more impressively, this structural design prevents bacteria from settling and forming biofilms without the need for toxic chemical coatings. In an industrial or healthcare setting, this 'structural' antibacterial solution reduces the need for harsh disinfectants and helps combat the rise of antibiotic-resistant bacteria, creating a safer and more cost-effective environment by mimicking the natural structures of shark skin.

When we turn our attention to environmental sustainability, the lessons from nature are even more profound, particularly regarding energy management in the built environment. A landmark example of this is the Eastgate Centre in Zimbabwe, which was designed by Mick Pearce to function like a termite mound. Termite mounds are marvels of natural engineering, maintaining a stable internal temperature even when external temperatures fluctuate wildly. By mimicking the complex network of vents used by termites, the Eastgate Centre utilises a passive cooling system that requires no conventional air conditioning. According to Wang *et al.* (2025), this building uses 35% less energy than similar structures in the region, illustrating how looking at an ecosystem level of design can lead to massive reductions in resource consumption.

Furthering this concept of ecosystem-level sustainability is the emerging idea of the Wood Wide Web as a blueprint for urban energy sharing. In a forest, mycorrhizal networks allow trees to share nutrients and information, where healthy trees essentially subsidise the survival of struggling ones through a decentralised fungal network. Rahubadda *et al.* (2025) proposed applying this mutualistic model to urban energy systems to create carbon-neutral cities. In this framework, buildings are not isolated units but are, instead, part of a three-layer network that includes on-site generation and peer-to-peer energy sharing. This mimics the biological principle of resource exchange to ensure that no energy is wasted and that the entire ecosystem remains resilient during peak demand or

power failures. This shift from individual consumption to networked sharing is a direct result of applying biological wisdom to human infrastructure.

Ultimately, the integration of biomimicry into industrial and environmental practices provides a sustainable competitive advantage for businesses and nations alike. A competitive advantage is sustainable when it cannot be easily replicated by competitors and provides long-term value. Biomimicry offers this by streamlining the front end of innovation, as researchers can bypass much of the trial-and-error phase by looking at solutions that have already been vetted by evolution (Kennedy & Marting, 2016). Companies that adopt these principles often find that they can decouple their growth from resource depletion, using less material and energy to achieve higher performance. This is particularly relevant as global regulations regarding carbon footprints and waste management become stricter.

2.7 Chapter summary

This literature review provides a succinct overview complimented by viewpoints core terminology associated with the nature of this research. In essence, the fundamentals of IE, environmental issues, environmental sustainability, forms of knowledge and the nuance of a sustainable competitive advantage are explored with nested literature topics deemed relevant. The IE profession has the potential to resolve many environmental issues using a sustainability narrative, co-design and creation of transdisciplinary knowledge and configuration of aspects that can be used to create a sustainable competitive advantage. There is limited research that integrates IE and environmental sustainability knowledge through transdisciplinary approaches to achieve a sustainable competitive advantage, particularly in developing country contexts such as South Africa.

It is imperative to mention that addition literature also features across the research design (chapter 3), publications (chapter 4-6 & 9), manuscript (chapter 7) and discussions (chapter 11). The following chapter provides the research design used to perpetuate this research.

Chapter 3

Research Design

3 Research Design

3.1 Introduction

This chapter will provide details on the research design configured using the research onion and Design Science Research (DSR). The research onion is then contextualised according to the needs of this research. A motivation for the selection of DSR as opposed to Action Design Research (ADR) is provided in section 3.3, before delving into the staged execution of DSR under set limitations and aligned to various ethical considerations. The design is used to explore the forms of knowledge components from IE and ES for an SCA. To better conceptualise the interaction between the research intent, scope and flow, Figure 18 was created.

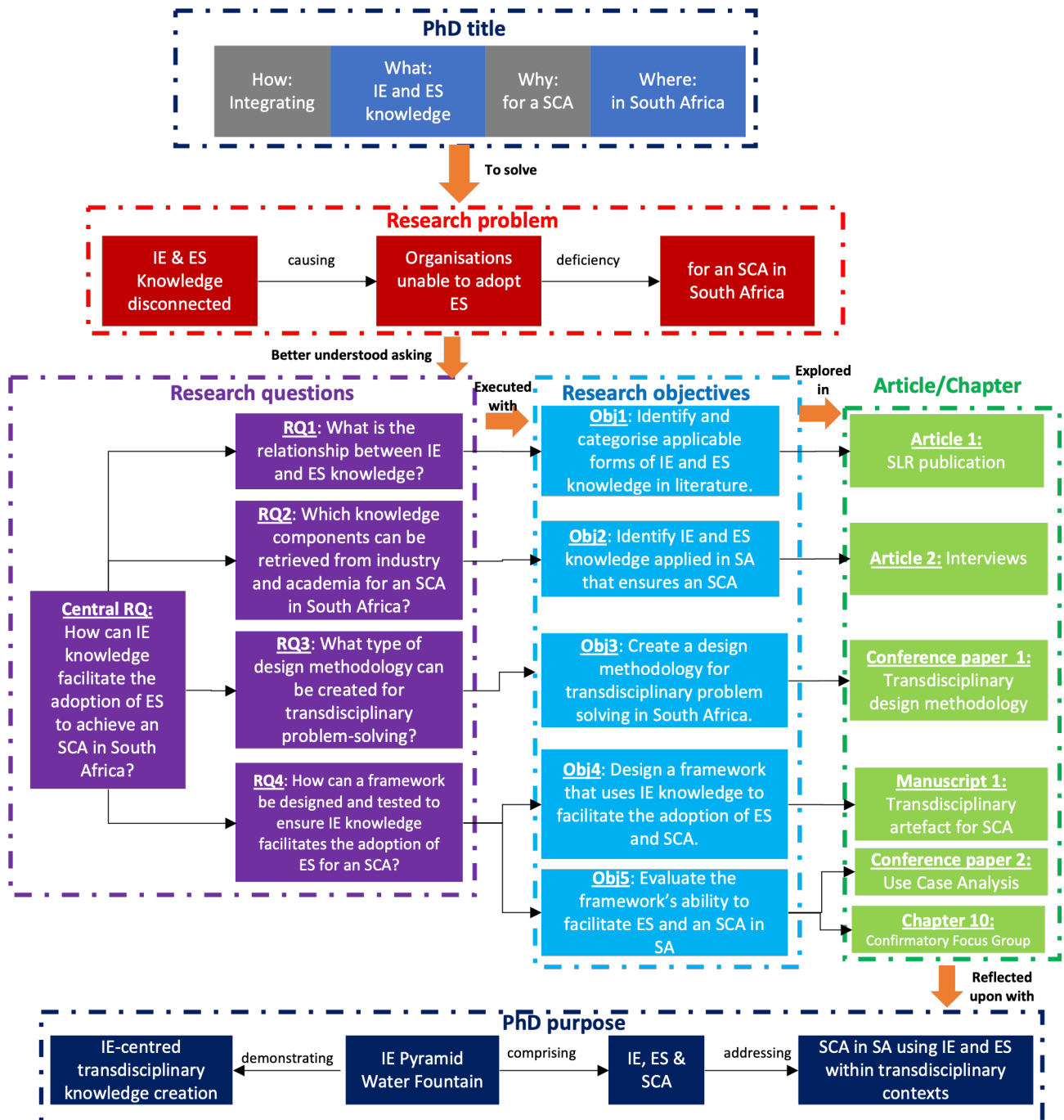


Figure 18: Research framework inspired by Darwish (2018)

Myriad tools and techniques are embedded into the nature of the study at the core of the research onion. The following dedicated subsections define and contextualise the research onion at distinct points in the research. Motivations for specific variations or forms of application also feature here to best motivate the research design employed.

3.2 Research onion layers

The work of Saunders *et al.* (2009) provides a comprehensive approach to plan and conduct research that entails an extensive research study. This approach is best described using the analogy of an onion with layers peeled away during the research journey. An illustration of this analogy is provided in Figure 19. The research onion is first explained to understand the layers of research. Various other research instruments include techniques and theories used to design the research. Once all these various elements are discussed, the research design and phases are presented in Chapter 3.

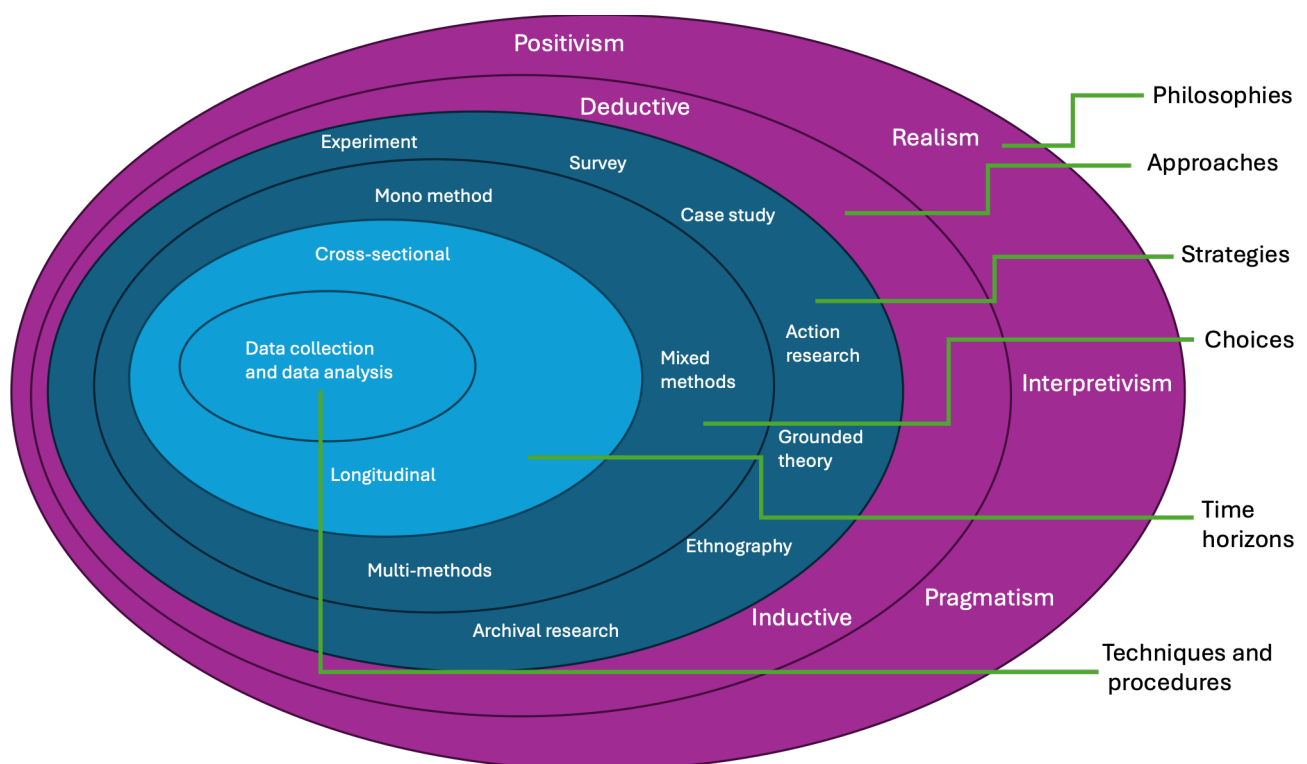


Figure 19 Research onion redrawn from Saunders *et al.* (2009)

3.2.1 Philosophies

The outer layer begins with the philosophy embraced in the research. Often, the inclusion of philosophical ideas influences the practice of the research while sometimes being hidden in research (Creswell & Creswell, 2017; Slife & Williams, 1995). This is also seen as the paradigm of research. Four frames of thought are positivism, realism, interpretivism and pragmatism. Positivism prides itself on discovering the laws of nature expressed through descriptions of theory focused on explanation and prediction in interdisciplinary fields of research (Park *et al.*, 2020). On the other hand, realism is concerned with understanding the world in its true state by focusing on structures and processes (House, 1991). Interpretivism was developed as a critique of positivism that considers context, human physical phenomena, recognising the differences in cultures by providing insights as opposed to the definite or universal laws (Alharahsheh, 2020). Pragmatism arises from

actions, situations and consequences and does not view the world as an absolute unity (Creswell & Creswell, 2017).

3.2.2 Approaches

The next layer of the research onion evaluates whether the research approach is inductive or deductive. Inductive approaches are most prevalent in qualitative data analysis, more so in grounded theory (Strauss & Corbin, 1990; Thomas, 2003). This form of research considers the development of summarised themes or categories derived from raw data. In contrast, deductive research is a top-down approach used as a logical approach that begins with a hypothesis developed from theory and later reasoning this from premises or propositions that are gathered from data (Babbie, 2020; Wilson, 2014).

3.2.3 Strategies

A range of strategies are prescribed by the research onion. These include experiments, surveys, case studies, action research, grounded theory, ethnography and archival research. Experiments involve the formulation of a hypothesis which is later tested in a laboratory. Experiments involve input and output relationships where a test or series of runs are evaluated against purposeful changes to the input variables of a particular system to identify and observe the output response (Montgomery, 2017). Surveys commonly involve the interaction with a sample of respondents from a well-defined population which includes individuals, households or organisations (Blair *et al.*, 2013). Case study research steers away from generalisation by closely examining people, topics, issues or programs to reveal unusual interactions, events, explanations, interpretations and cause-and-effect connections (Hays, 2003). Action research, also referred to as practitioner research, is research concerning self-reflection by learning and through action and reflection (McNiff, 2013). Action Research is applied often in engineering spaces to design and evaluate frameworks, examples of which include applications in construction engineering and information systems development (Azhar *et al.*, 2010; Burstein & Gregor, 1999).

Grounded theory is an inductive, qualitative research methodology that discovers and creates new theory grounded in data that stretches into various disciplines including nursing, health sciences, computer sciences, marketing, social psychology and education only to mention a few (Martin & Turner, 1986; Tarozzi, 2020). Archival research can create longitudinal data by improving the validity and reliability of new theories using existing datasets (Welch, 2000).

3.2.4 Choices

The choice of research can embody a qualitative, quantitative or mixed-methods choice or method of execution. This is dictated by the nature of the study, the problem, the aim and the intended artefact or solution. Fossey *et al.* (2002) define qualitative research as a methodology that explains experiences, behaviours and social contexts in the absence of statistical procedures or quantification (Corbin & Strauss, 2014), whereas quantitative research makes use of the latter.

Poth (2018) discusses the complexities in defining mixed methods research, mentioning that it is an innovative research approach that integrates various qualitative and quantitative data sources, collection methods, and analysis strategies by accounting for research conditions and contextual influences in the research.

3.2.5 Time horizons

The research onion stipulates that time horizons in research can be longitudinal or cross-sectional. According to Johnson (2010), longitudinal studies involve repeated observations over a determined time period whereas cross-sectional studies consider the data collection at one time instance. The selection of the time horizon is dictated by the nature of the design, the research objectives and the resource constraints.

Longitudinal studies assist with validating concerns and can, in some cases, be compared with cross-sectional data to reaffirm assumptions made in the research and its results (Rindfleisch *et al.*, 2008). The application of longitudinal studies is not foreign to engineering. Brainard and Carlin (1997) conducted a longitudinal study to track female undergraduate women pursuing degrees in science and engineering. The methodology made use of a blend of six variations of surveys and questionnaires to acquire persistence factors that helped determine retention rates. This study demonstrates the relevance and applicability of surveys for longitudinal studies within engineering contexts. Cross-sectional studies can assist with policy decisions by critiquing the regional and instantiations of events under scrutiny (Markovitz *et al.*, 2012). This time horizon is particularly valuable with analytical and quantitative methods tied to assessing environmental performance and sustainability practices (Cowan *et al.*, 2010; Popescu *et al.*, 2017).

3.2.6 Techniques and procedures

At the core of the onion lies the discipline-specific tools and procedures. The list of data collection and analysis techniques or procedures is plentiful; therefore, a careful selection must consider the problem, context and subject matter. This is further explored in the subsections to follow.

3.3 Contextualised research onion

Figure 20 provides a rendition of the research onion analogy with the case-specific application in this study. This builds on the various class definitions previously discussed in Chapter 2.

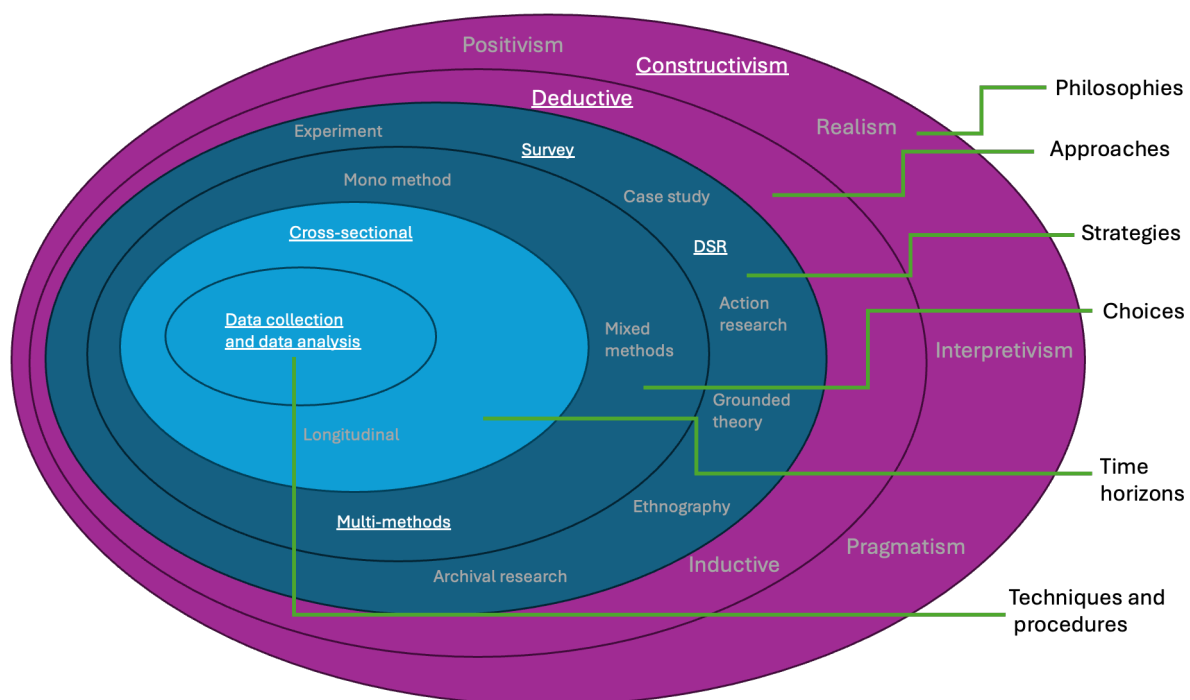


Figure 20 Contextualised Research onion

This configuration also complements the TD nature of this research. Following the discussion on data analysis processes by Azungah (2018), the use of a start list with the thematic analysis (TA) approach employed in this research warrants the research approach as deductive since it builds on the knowledge components that will be gathered and interpreted. It is therefore for this reason that a deductive approach is used to code the systematic literature review full-text publications, interview transcripts and apply Pareto-Weighted Thematic Analysis, as explained in section 3.7. This research will adopt DSR (in addition to the research onion) as the strategy, with a survey approach for the interviews and survey statements used in the Confirmatory Focus Group (CFG) and Use Case Analysis (UCA) (Mangaroo-Pillay et al., 2022; O'Raghallaigh et al., 2012). This is further motivated in section 3.3.

The choice of research takes on a multi-methods approach which begins with a qualitative approach by analysing textual information obtained from the SLR and Interview transcripts. This is sequenced by the inclusion of quantitative data in two instances. The first is harvested from the code densities retrieved from the SLR and interview data. The only quantitative data is from the densities used for the Pareto principle (discussed in section 3.6) and the ordinal data the Likert scale creates from the survey during the CFG (section 3.7,) which is used to evaluate the framework.

This is not sufficient to warrant the study being classified as mixed methods research, but rather a multi-method study since it entails various methods applied at different stages in the research. This, according to Kasirye (2024), is a valid approach to create a distinction between mixed methods and multi-method. The time horizon stands to be cross-sectional since the SLR explores literature fat a defined time period. The same can be said for interview data and the confirmatory focus group interaction which all occur at distinct points in time and not over a long period. The interviews draw upon the real-life experiences and knowledge of more than 4 years. The use case analysis and the confirmatory group also evaluate the framework at one instance. To design the framework, a design methodology first needs to be created to ensure that the artefact correctly harnesses IE and ES to provide transdisciplinary problem solving and sustainability. The use case analysis provides four scenario applications of the TD artefact designed in study and measured against SDGs, the African Union 2063 Goals and South African environmental sustainability Frameworks and metrics closer to legislations and policies promulgated.

For this research, the link between IE and ES will be explored to develop a TD framework for a SCA in South Africa. This framework will reflect on IE and ES knowledge components that can be used to create an SCA. The myriad discipline-specific techniques and procedures employed in this study feature at different stages of this research. Table 5 demonstrates the various research components linked to each stage of this research.

Table 5 Research design summary

Research component	Stage 1	Stage 2	Stage 3	Stage 4
Problem:	Knowledge from IE and ES domains currently lacks a formal, visible and intuitive classification without a transdisciplinary integration to successfully achieve an SCA in South Africa.			

Research component	Stage 1	Stage 2	Stage 3	Stage 4
Aim:	This study strives to improve the formalisation, visibility, classification, or transdisciplinary integration of IE and ES knowledge to achieve a SCA in South Africa.			
Objective(s)	(1) Identify and categorise applicable forms of IE and environmental sustainability knowledge in literature	(2) Identify hybrid IE and environmental sustainability knowledge applied in South Africa that ensures a sustainable competitive advantage	(3) Create a TD problem solving methodology for TD artefact creation (4) Design a TD framework that facilitate a sustainable competitive advantage by integrating IE and Environmental sustainability knowledge	(5) Evaluate the adoption framework to promote a sustainable competitive advantage in South Africa
Method	Systematic Literature Review (SLR) and a Thematic analysis	Interview industrial engineers and environmental managers or practitioners in South Africa	Create a TD design methodology for South Africa Apply the design logic to create and test the TD artefact by applying Pareto-Weighted Thematic Analysis on preceding findings	Carry out a Use Case Analysis to evaluate the artefact against SDGs & Africa Union Goals Perform a Confirmatory Focus Group (CFG) which will evaluate the data consolidation of the knowledge components, design logic and final artefact from the study.

Research component	Stage 1	Stage 2	Stage 3	Stage 4
Dataset	Research publications according to a search protocol	Industrial Engineers and environmental managers and practitioners in South Africa.	Design methodology Preceding knowledge components from SLR and interviews	Initial sample used in the interviews will be invited to partake in the study once more since much of their insight and considerations were informed by their insight and contribution. Use case analysis using sustainability-orientated metrics and frameworks
Intended artefact	Thematic analysis based on SLR search protocol filtered results	IE knowledge components that share a relationship between IE and environmental sustainability	TD artefact methodology TD artefact for SCA in South Africa	Validated framework via surveys and use case analysis

The execution of the design will first require a consideration between DSR and ADR discussed in the following subsection.

3.4 Selection between DSR and ADR

Design Science Research (DSR) and ADR were two top contenders for the selected research strategy since both of them are strongly associated with addressing ES issues. DSR is more focused on socio-environmental challenges, whereas multi-stakeholder engagement is better facilitated with ADR (Dooley, 2024; Zare et al., 2024). Other research strategies that were considered include the Critical Artefact Methodology (CAM) and soft systems thinking. Although CAM creates stakeholder engagement, its validity concerns for impactful sustainability research are in question (Bowen, 2009b). Another shortcoming of CAM is that the methodological clarity is vague since it requires creativity stakeholders might need to be trained on since it uses methods and concepts which are unclear and difficult to adopt (Bardzell & Bardzell, 2013; Bowen, 2008). After considering soft systems thinking, it was found that it does not account for the moral perspective on ecological restoration (Palmer et al., 2009). Zexian and Xuhui (2010) argue that soft systems thinking has extreme subjectivism and is a conservative system concept as a theoretical weakness. Given the methodological clarity, pragmatist lens and need for impactful sustainability research, DSR and ADR are better suited.

Beyond its theoretical grounding, the selection of Design Science Research (DSR) for this study is justified on practical, artefact-development grounds. Hevner et al. (2004) argue that design-science research is fundamentally distinguished from behavioural-

science research by its orientation toward creating and evaluating a purposeful artefact intended to solve an identified organisational problem, rather than merely explaining or predicting behaviour. Their three-cycle view of DSR is instructive here: the relevance cycle requires that the research be anchored in a genuine application-context problem and that the resulting artefact be assessed for its practical utility within that environment, while the design cycle demands iterative build-and-evaluate activity on the artefact itself. This positions artefact construction, not theory alone, as the primary vehicle through which research contribution and rigour are demonstrated. Peffers et al. (2007) reinforce this practical orientation by formalising DSR as a structured process explicitly centred on designing and developing a value-adding artefact, demonstrating its use in a real or realistic context, and evaluating the extent to which it meets pre-defined objectives. For this study, which seeks to produce a usable transdisciplinary model integrating industrial engineering and environmental sustainability knowledge, DSR is therefore appropriate not simply because it accommodates theoretical reasoning, but because it obligates the researcher to build, demonstrate and evaluate a working artefact whose practical utility can be assessed by the practitioners and organisations it is intended to serve.

Each ADR phase could be used to correspond with each stage of this research. To aid in formulating the problem, the findings from the thematic analysis will indicate the relationship between IE knowledge and ES. To build and evaluate this, experts will provide the knowledge components that complement IE or ES knowledge for an SCA in South Africa. To reflect further, this is categorised by mapping the interactions between the results from Stages 1 & 2 outlined in Table 3. These results are then subjected to creation of the TD methodology to create the artefact. Once carefully understood, these will form the basis for a framework (designed in Stage 3) which will be evaluated via a CFG, which will entail a survey and discussion on topics concerning the artefact for verification and validation purposes in Stage 4.

Most arguably, DSR is the more favourable research strategy since it focuses more on developing generalizable knowledge about design processes and artefacts (Piirainen & Briggs, 2011). Alessandro et al. (2017) believe that the inclusion of design theories can enhance the transparency and rigor of the knowledge obtained from DSR. This approach was achieved by Llieva et al. (2022) who adapted biomimicry into a “biomimicry for sustainability” framework. This study is inspired by this approach and will thus embed the design cycle with constructs and design criteria for frameworks focused on ES.

Design Science Research (DSR) is an inherent problem-solving process (Hevner et al., 2010). Rooted in systems development with multi-methodological approaches, four research strategies focus on theory building, experimentation, observation and systems development (Hevner et al., 2010; Nunamaker Jr et al., 1990). Multiple scholars later refined the concept and created four possible entry points for DSR: problem-centred initiation, objective-centred solution, design and development-centred initiation and client/context initiation (Hevner et al., 2010). An illustration of the four-cycle DSR framework is provided in Figure 21.

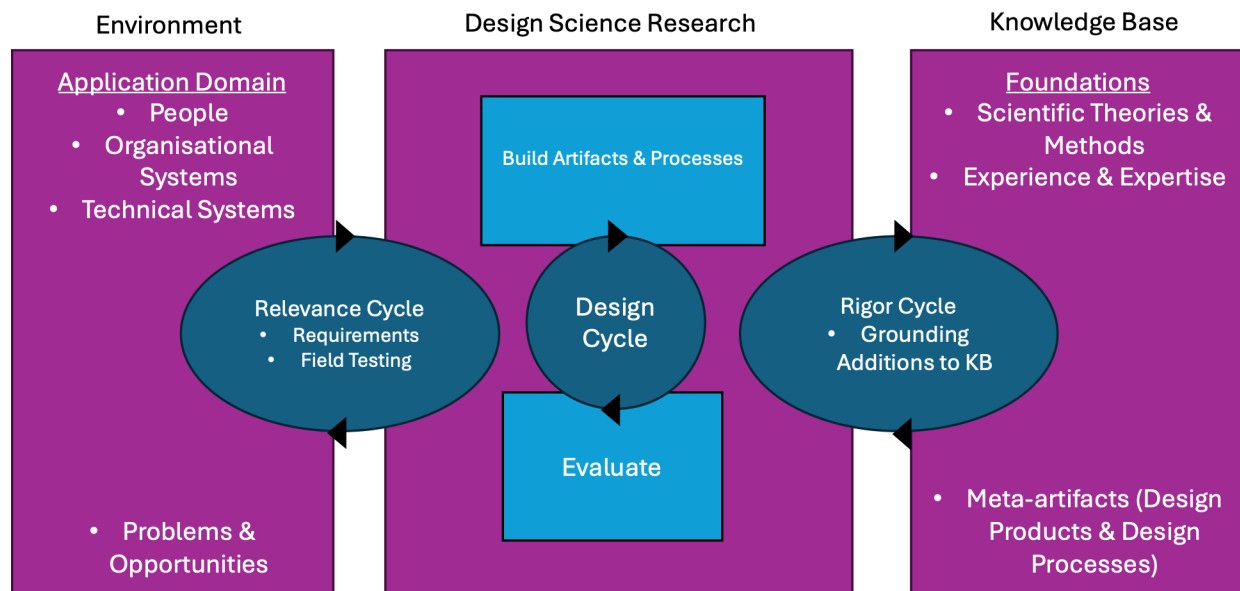


Figure 21 Design Science Research Cycles redrawn from Hevner *et al.* (2010)

As can be observed, the relevance cycle serves as the context initiation, whereas the design cycle is invested in the design and development-centred initiation. The rigour cycle speaks to the problem-centred initiation and objective-centred solution.

To represent the trajectory and execution of this research, Figure 22 depicts the research design for this study. The corresponding chapter numbers (Ch) for the thesis with the planned research articles and the objectives (Obj) have also been linked with set areas within the DSR framework.

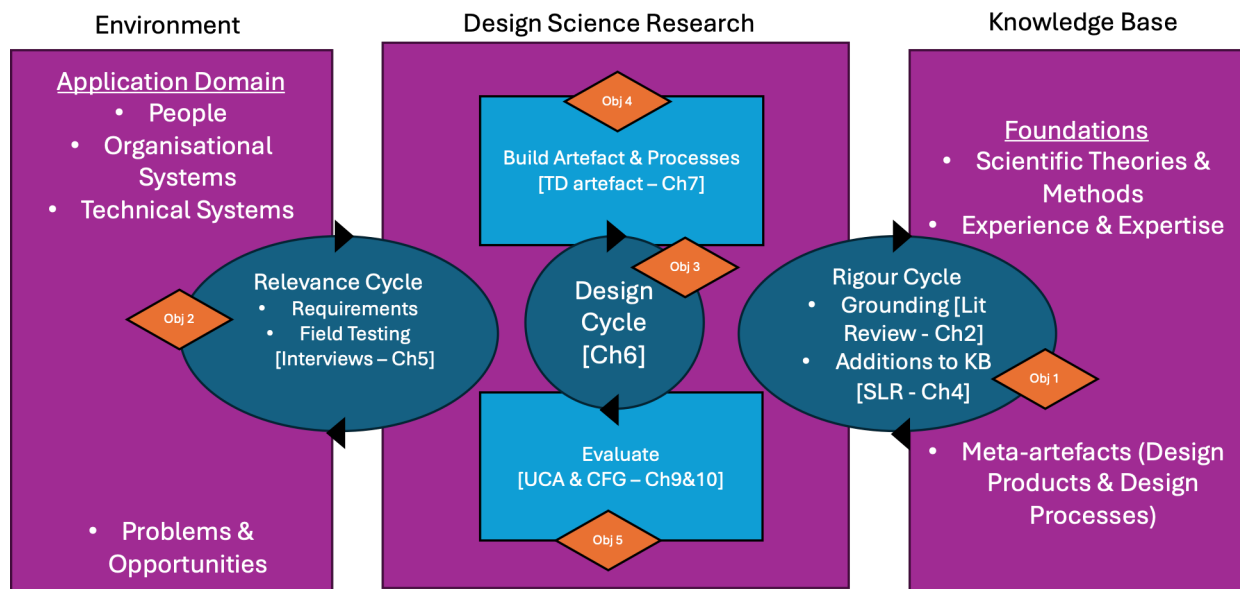


Figure 22 DSR applied in this research adapted from Hevner (2007)

This study will transition from high to low levels of abstraction. To demonstrate this process with the DSR approach in mind, Figure 23 shows the four stages of the research with the dedicated chapters.

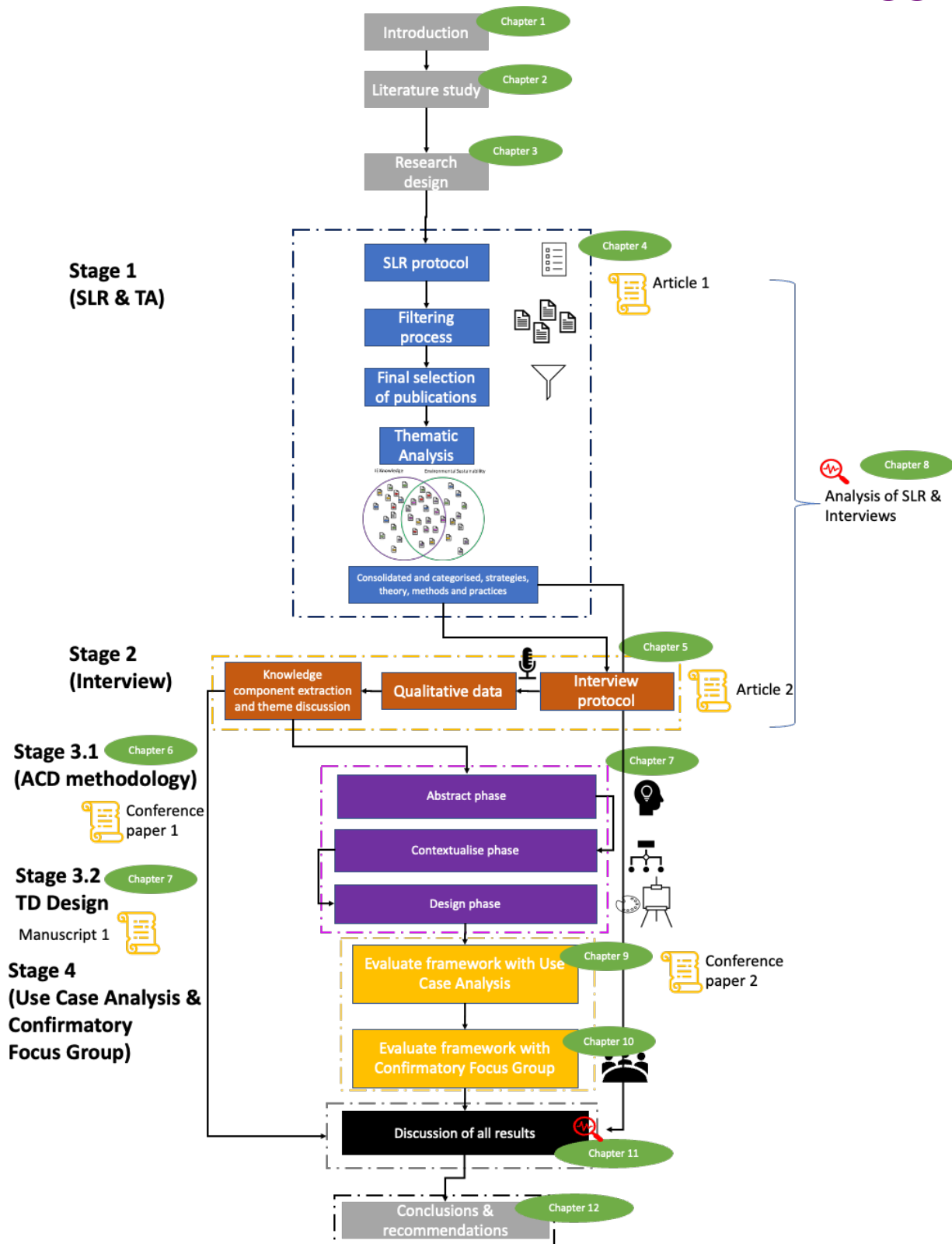


Figure 23 Research design with DSR staged with chapter outline and techniques

The highest form begins with the SLR and thematic analysis in Stage 1, and the rigour cycle of DSR. Stage 1, rigour cycle meets the first objective (SLR and ATA). Stage 2, relevance circle meets the 2nd objective (interview). The design cycle (with design methodology as Chapter 6) will have phase 3 (build design artefacts & processes). This is important for the TD artefact presented using Chapter 7 and objective 4 by means of

the TD design methodology (objective 3). The 2nd part of the design cycle is the 5th objective and evaluation phase 4 by means of a use case analysis (Chapter 9) and confirmatory focus group (Chapter 10). Additional analysis features in Chapter 8. Chapter 11 serves as a discussion before Chapter 12 concludes the study.

3.5 Stage 1 (Rigour cycle)

A SLR is a rigorous means of identifying, planning and producing an explicit and reproducible synthesis of literature developed by academic scholars and practitioners (Fink, 2019). The most generic stages for an SLR are (1) planning, (2) conducting and (3) reporting of the review (Alexander *et al.*, 2019).

The purpose of an SLR is to identify, interpret and analyse published research literature to extract meaningful insight concerning a prevalent issue (Fink, 2019). This coincides with a similar definition from Xiao and Watson (2019), who state that an SLR should describe, test, extend or critique a body of literature in order to unearth new meaning.

Various forms of Literature Reviews exist. So much so, that each form is recognised as a standalone with set descriptions. The various types of SLRs are (Xiao & Watson, 2019):

- a) Critical – critical evaluation of literature quality using a hypothesis or model from in-depth analysis and conceptual innovation
- b) Integrative – experimental and non-experimental methods based on findings from empirical and theoretical literature with a phenomenon
- c) Literature review – current literature on a range of academic interests
- d) Mapping review/systemic map — literature to identify future research avenues
- e) Meta-analysis – a statistical approach to quantitative studies to quantify the implications of the results.

This study will follow the rigorous SLR method, as described by Albliwi *et al.* (2014). The method consists of three phases: planning, conducting, and documenting. The steps within these phases are detailed as follows (Albliwi *et al.*, 2014):

A. Planning the review

- Step 1 – Research purpose and objective clearly defined
- Step 2 – Develop research protocol with the appropriate inclusion criteria, exclusion criteria, databases to be searched, keywords and quality assessment criteria.

B. Conducting the review

- Step 3 – Establish relevance criteria and apply this to the studies
- Step 4 – Search and retrieve the literature from electronic databases
- Step 5 – Selection of studies based on the inclusion and exclusion criteria.
- Step 6 – Quality assessment for relevant studies
- Step 7 – Data extraction from selected literature
- Step 8 – Synthesis of studies (analysis) to extract facts and conclusions from the selected literature.

C. Documenting the review

- Step 9 – Reporting on SLR findings
- Step 10 – Dissemination by publishing SLR findings in an academic source.

Some of the advantages of SLRs are that they aid in identifying research gaps in literature and aid in suggesting future research directions (Gough & Richardson, 2018). It is widely recognised that SLRs are a rigorous way of critiquing a body of literature in a way that provides insight and perspective associated with a particular research problem (Armitage & Keeble-Allen, 2008; Massaro *et al.*, 2016).

One of the shortcomings of SLRs is the reproducibility of their results as expressed by Maggio *et al.* (2011). To mitigate this, substantial effort must be made to clearly define clear research objectives, search strategies and inclusion and exclusion criteria for accurate interpretation and reporting (Thompson *et al.*, 2008).

An SLR is often prompted by strict planning, resulting in the formulation of a research protocol (discussed further in Table 6). This details specific inclusion and exclusion criteria that will be used to screen and identify relevant literature that will be subjected to the thematic analysis.

For Stage 1, the search protocol from the SLR (Table 6) will be used to define the volume and final selection of research publications that will be further analysed in the study.

Table 6 SLR search protocol

Search component	Specifications	Rationale
Keywords	Industrial Engineering, Environmental Sustainability	Key terms relevant to the purposes of this study
Platforms	Science Direct, Scopus, IEEE Explore, Web of Science, EBSCO host, Emerald Insight	Reputable academic databases accessible to the researcher
Search strategy	“Industrial Engineering” AND “Environmental Sustainability”	Boolean operator for the union of the content. Wildcards are not considered.
Time frame	Unbounded until 2021*	Track co-citations and knowledge growth across the databases
Inclusion criteria	Publications discussing theory, concepts, methods, strategies and techniques that achieve or promote environmental sustainability	Screen publications to conform with the scope of the study
Exclusion criteria	Publications that are not in English, undergoing review.	Protect the academic integrity and ability to analyse the research publications according to the aim of this study
*Kindly note the 2021 year was fixed when the analysis began		

The thematic analysis will be conducted in atlas.ti, where emergent themes will be used to code the research publications. Systematised by Braun and Clarke (2006) through a rigorous six-phase framework, thematic analysis evolved from an implicit background technique into an explicit, widely cited method for constructing analytic themes across semantic and latent levels. Its defining strength lies in its theoretical flexibility, allowing application across diverse disciplines without committing to a single epistemological position. In refining their approach as "reflexive thematic analysis," Braun and Clarke (2019) reaffirmed that theme development is an inherently subjective, interpretive process where researcher positionality is an analytic resource rather than a bias to be eliminated through inter-coder reliability. This approach will be used to identify co-occurrence and graphically represent relationships between codes (themes) within a set of data (research publications) (Guest *et al.*, 2012). The SLR results and findings from this first stage have been published in the journal Sustainability. These results also unpack the themes and demonstrate the relationship between IE and ES. The publication features as a standalone Chapter 4. It is imperative to note that the findings from this stage will form the basis for Stages 2 – 4. The same can be said for the thematic analysis, which is applied to the SLR findings and interview transcripts. This is later incorporated into the design of the TD artefact using the design method developed in Stage 3, using a new Pareto-weighted thematic analysis technique created for this research. The coding was performed by the researcher within the atlas.ti environment.

3.6 Stage 2 (Relevance Cycle)

For Stage 2, interviews are performed. Interviews are an effective means of constructing knowledge using the simultaneous exchange of ideas between the interviewee(s) and interviewer (Kvale, 1996). Interviews allow the researcher to extract in-depth insights into the complex subject matter by reporting on the varying viewpoints, experiences and opinions of the interviewees (Hillman, 2022; Opdenakker, 2006).

The four most common forms of interviews include structured, unstructured, semi-structured and focus group interviews. Table 7 takes inspiration from Alsaawi (2014) and provides a description and associated shortcomings for each interview type:

Table 7 Summary of interview types with shortcomings informed by Alsaawi (2014)

Type of interview	Description	Shortcoming(s)
Structured	Controlled acquisition of information using planned interview questions	Limited in-depth data, limited variation in data and limited interviewer flexibility (Dornyei, 2007).
Unstructured	That is best suited for gathering information on a specific phenomenon where one question is used to guide an extensive response from the interviewee	Unpredictable directions with limited control over the type and quantity of information. This often leads to large amounts of data.

Semi-structured	Mix of planned questions that are open-ended to create case-specific questions impromptu	There is varying control over the depth and richness of responses which often calls for the questions to first be piloted
Focus group	This follows the application of either a structured, unstructured or semi-structured interview involving six to twelve interviewees. This generated high quality data and follows a brainstorming format.	Difficult transcribe and confidentiality of participants cannot be guaranteed. It can lead to contentious debate which may require a moderator, and questions are fewer than the other forms of interviews.

Structured interviews are suitable in instances where the type of information is not known to the researcher (Alsaawi, 2014). Considering the complexity of environmental sustainability problems, structured interviews are befitting to best understand the link between IE and ES in South Africa.

To build reliability in the interview, an interview protocol as discussed by Creswell and Creswell (2017) will be used. Not only does this serve as an interview guide, but is used to safeguard consistency (Brewster *et al.*, 2015). This is made possible by the research questions which are informed by the SLR. In this research, the results from the SLR will be used to construct the research questions that address themes identified in advance (Kvale, 1996). As succinctly summarised by Azungah (2018), this already organizes interview data for analysis and interpretation (Bowen, 2009a). In this research, the categorisation will follow strategies, theories and methods and practices that speak to the three business execution levels.

Another important consideration is the sample size for an interview. The sample size justification for an interview is subject to various factors. The work of Vasileiou *et al.* (2018) reflects on the sample size of qualitative interviews. The fundamental principle used to ascertain the sample size is by means of saturation. Having originated in grounded theory, which is linked to theoretical sampling, data is collected and analysed to develop theory. Theoretical saturation or grounded theory saturation, is more specific to theoretical categories and not the data at hand (Vasileiou *et al.*, 2018). Theoretical saturation therefore occurs when there are no new sparks of theoretical insights or properties to your core theoretical categories (Charmaz, 2014). In this instance, it means that there is an adequate sample. Perhaps more prescriptively, an estimate of participants should be between 20-30 participants or fewer if saturation has occurred (Creswell & Creswell, 2017; Guest *et al.*, 2006; Hennink *et al.*, 2017). In the research conducted by Francis *et al.* (2010), various adaptable principles are proposed in order to decide on data saturation. Two main principles are proposed, namely a) researchers must specify an initial analysis sample which they wish to target, and b) stopping criteria must be determined – a set number of additional interviews which yield no new themes or ideas. This will also accompany more features from the study that will be used to conclude the sample size used in this research.

Blair *et al.* (2013) report on various forms of sample bias that could present themselves in survey research, sample, selection and nonresponse bias. Coverage bias is when a segment of the population is improperly excluded. Therefore, strict population

characteristics will be used where the same initial population and more will be used to evaluate the adoption framework. For selection bias, a standard email approach will be used, therefore creating equal chances of selection since most academics or practitioners engage in email communications (Askalidis *et al.*, 2017).

The last form of bias is nonresponse bias, where there could be a failure to respond given a multiplicative function of the nonresponse rate and different between respondents and nonrespondents (Garrett *et al.*, 2010). To mitigate this risk and reduce the chances of this, efforts will be made to have the initial interview sample group partake in the survey and by their recommendation (via snowballing), convey the study clearly and prompt for more evaluation by practitioners (Gummer & Blumenstiel, 2018).

In this research, an interview protocol has been developed and provided in Table 4. The protocol lists various questions derived from the findings from Stage 1. This will be used to explore the relationship between IE knowledge and ES knowledge components which include strategies, theories, methods and practices. Questions will seek to identify possible knowledge components that complement both IE and ES. Participants will also have access to the results uncovered in Stage 1, as contexts to aid them in answering the questions if they request so.

A snowballing technique will be used, beginning with an initial sample set of 15 participants. According to Ting *et al.* (2025), snowballing is a prime approach to help identify a hidden population, increase sample diversity, minimise forms of bias, and enhance the quality of data, particularly in business and management studies. As previously mentioned, industrial engineers and environmental managers and practitioners in South Africa will be contacted using an independent researcher who will also share an informed consent form having obtained ethics approval. It is important to note that since this study also explores creating TD knowledge, individuals from academia and industry form part of the population. These will be identified from LinkedIn and networks known to the researcher and promoter. This is under the advice of Robinson (2021), who advises using LinkedIn to interview limited sample sizes difficult to find. The snowballing technique complements this by extending beyond these known networks, especially when the population is limited (Sadler *et al.*, 2010). Only after obtaining informed consent, will interviews be conducted via MS Teams. The interviews will take 30-45 minutes and participants will be able to withdraw from the study at any stage. The protocol has been presented in Table 8.

Table 8: Research protocol adapted from Creswell and Creswell (2017)

Interview protocol to investigate the relationship between industrial engineering knowledge and environmental sustainability
Introduction: This research identifies the relationship between industrial engineering and environmental sustainability knowledge components. This study is a first in a series of studies contextualising industrial engineering knowledge in terms of its applicability to environmental sustainability. It considers how Industrial Engineering (IE) can act as a catalyst in creating new forms of transdisciplinary knowledge areas. It also considers how industrial engineering knowledge can contribute to environmental challenges. You have been identified as a candidate because you are an industrial engineering or environmental manager or practitioner in South Africa. Some of these questions explore the relationship between industrial engineering (IE) and environmental sustainability

(ES). There are three questions. For each question, you can also request more context, in which case the researcher will provide more details from an earlier phase of this research.

Main research question: What is the relationship between IE knowledge and environmental sustainability knowledge?

Question 1: What strategies can you identify that share a relationship between (are applicable to both) IE and environmental sustainability that ensure sustainable competitive advantages?

Probing questions: What Environmental sustainability strategies can be linked with IE? How do some of strategies facilitate environmental sustainability?

Question 2: What theories can you identify that share a relationship between / (are applicable to both) IE and environmental sustainability that ensure sustainable competitive advantages?

Probing question: What environmental sustainability theories can be linked with IE?

Question 3: What methods and practices can you identify that share a relationship between (are applicable to both) IE and environmental sustainability that ensure sustainable competitive advantages?

Probing question: How do some of these facilitate environmental sustainability?

The results from each interview will be completely anonymised. The only characterising question that will be posed is to ask the participant to kindly indicate the number of years they have spent in their predominant industry. This is to also help motivate and back the experience and quality of the results obtained during the interviews.

In accordance with the interview sample size saturation principles discussed in Chapter 2, Table 9 provides the specific saturation identifiers that will be used in the study.

Table 9 Saturation identifiers employed in this research

Saturation principle	Application to study
a) Initial analysis sample	An initial analysis sample of 15 interviews will be identified.
b) Stop criteria	A sample size of 3 additional interviews will be conducted in an instance where one of the following events occur: i. Participants recommending already interviewed participants to be included in the study on two occasions ii. Code frequencies greater than two or more knowledge components under a strategy, theory and method or practice

Each interview will be recorded on MS Teams in conjunction with the transcription feature. The raw transcript will be edited, anonymising the interviewee's identity. Further details on the research method, rigour and reliability techniques and the results are presented in Chapter 5.

Similar to Stage 1, thematic analysis will be reintroduced. However, this time with Sankey diagrams created in atlas.ti.

Sankey diagrams are also incorporated as a means of analysing the research. The Sankey diagram traces its origins to the field of engineering, where it was first employed to depict the thermal efficiency of a steam engine. The technique gives homage to Captain Matthew Riall Sankey, an Irish engineer whose 1898 diagram visualised the energy losses of a steam engine. It demonstrates flow widths proportional to quantity, establishing the core convention that continues to define the format where directional arrows have thicknesses scaled to the magnitude of the flow they represent (Schmidt, 2008). Schmidt (2008) situates this innovation within a broader nineteenth-century tradition of flow-based graphical representation, tracing precursors in the work of engineers concerned with communicating quantitative flow relationships without resorting to tabular data. The novelty in Sankey's work was its explicit accounting logic since the flow width is proportional to quantity, the diagram enforces a visual conservation of mass or energy, allowing losses and inefficiencies to be identified immediately rather than inferred from numerical comparison (Schmidt, 2008).

From the 1990s onward, the Sankey diagram was substantially repurposed by the industrial ecology and material flow analysis communities, which recognised that its mass-conservation property made it a natural fit for tracking resource flows through industrial and economic systems (Schmidt, 2008). In this second phase of development, the diagram evolved from a single-process illustration into a systems-level tool capable of representing multi-stage material and energy flows across entire production chains, national economies, or urban metabolisms. Schmidt (2008) documents how software-based generation of Sankey diagrams enabled analysts to construct increasingly complex flow networks, incorporating branching, recombination, and loss terms at each node, while preserving the underlying accounting discipline established a century earlier. This methodological maturation coincided with growing policy interest in resource efficiency and life-cycle assessment, for which the Sankey diagram offered an intuitive means of communicating where material or energy value was lost, recycled, or exported from a system boundary. The diagram's capacity to render abstract quantitative relationships immediately legible to non-specialist audiences has been central to its adoption in sustainability reporting, energy auditing, and industrial ecology research more broadly (Schmidt, 2008).

More recently, the Sankey diagram's core logic, flow, magnitude, and conservation have been extended well beyond its original energy and material flow context into domains concerned with more abstract forms of movement or transition. Templ *et al.* (2025) demonstrate its application to curriculum planning in higher education, using flow diagrams to visualise student progression and module selection pathways in ways that mirror the structural logic of material flow analysis while communicating an entirely different kind of data. Similarly, Sankey-based visualisation has been adapted for

bibliometric analysis, where publication, citation, and thematic clustering patterns are rendered as proportional flows between categories. This allows researchers to identify dominant pathways within large corpora of literature. These extensions illustrate a more general property of the Sankey diagram that is well suited to any analytical context in which a reader needs to compare the relative size of multiple pathways irrespective of their entity. This generalisability, from nineteenth-century thermodynamics to twenty-first-century curriculum analytics, underscores the enduring analytical value of a visualisation technique whose fundamental grammar has remained essentially unchanged for over a century.

3.7 Stage 3 (Design cycle build artefact)

For Stage 3, a transdisciplinary knowledge creation methodology by Roopa, 2024 will be used (Chapter 6). This methodology is used for high-level abstraction for problem-oriented research similar to Gregor *et al.* (2013). This methodology has been used for TD knowledge creation, where a lighthouse model was designed for TD problem solving and sustainable development in South Africa. The methodology uses solutions termed solution fragments to sequentially piece together an intended artefact using a symbol of inspiration. It is for this reason that this methodology has been selected, since it helps create transdisciplinary knowledge and creates an artefact relevant to South Africa that is grounded in problem-orientated research. It therefore also complements the DSR approach employed in this research. The three stages of this method have been provided as follows (Roopa, 2024):

- a) Abstract: solution fragments are obtained once a symbol, icon, artefact or analogy is obtained. This application of abstraction aids in simplifying complex relationships (Hoover *et al.*, 1991). This abstraction exposes a range of solution fragments that mimic functions, retrieve literature, sidestep critiques and emerge from brainstormed ideas.
- b) Contextualise: relate solution fragments within the context of the problem or source of abstraction. This entails case-specific circumstances, methods of application and characteristics belonging to the subject matter or geography in which the problem is situated. The contextualisation is applied to the problem or the assortment of solution fragments.
- c) Design: The solution fragments obtained during the preceding phases are consolidated and used to design the intended artefact. The solution fragments can translate to features or attributes that belong to the entity identified in the abstraction phase. The contextualisation ensures that the design is case-specific.

There is no sampling strategy involved with the solution fragments, but rather the use of preceding results which are amalgamated and clustered. The various knowledge components from the SLR (Stage 1) and interviews (Stage 2) are deemed the solution fragments that are merged. It is assumed that contradictions between the literature and the interview participants' data will emerge since different datasets will classify knowledge components at more than one business execution level. Therefore, weightings will be used alongside text similarities to address any contradictions. This will also be used to filter out the number of knowledge components and possible pairings between the various strategies, theories and methods and practices. Each citation from the literature (each specific research paper from the last stage of the SLR) and each participant will each be assigned a weighting of 1.

All the various knowledge components from each business execution level will be merged. To filter and obtain the most relevant knowledge components, the Pareto principle will be employed. A Pareto analysis will be performed across each consolidated range of knowledge components. Therefore, each strategy, theory and method and practice will be Pareto-sliced according to the 80/20 principle by calculating cumulative weights determined from the code density citations in literature and participant frequencies during the interviews.

The various knowledge components will be sequentially paired using a top-down approach down the three business execution levels with intermediate PWTAs. Strategies will first be matched with theories. The pairings will not be one-to-one since several theories may suit more than one strategy. The same notion stands for all pairings. After establishing the links between the strategic and tactical levels (strategies with theories), the Pareto principle will be applied using the cumulated densities that add the weights of each specific strategy and theory pairing. The same process is repeated to pair the combination of strategies and theories with a specific method or practice. The final Pareto slice will be applied to the combination of these three knowledge components for each concept. These will all be visualised using alluvial diagrams since they demonstrate the flow of principles using the cascading application stream argued in this research.

The amalgamation of these results will be used to design a framework that facilitates a sustainable competitive advantage using IE and ES knowledge. The design will also rely on requirements based on the core theory domains that emerge from the research. This artefact will be evaluated in Stage 4.

3.8 Stage 4 (Design cycle evaluate artefact)

For Stage 4, Use Case Analysis (UCA) and Confirmatory Focus Group (CFG) are employed. This is used to verify and validate the TD artefact.

3.8.1 Use Case Analysis

Traditionally, a Use Case Analysis (UCA) is implemented in software solutions, more so during its developmental stages (Schneider & Winters, 2001). It is commonly understood that UCA aids in clarifying requirements, designing and testing frameworks (Zhu & Tsai, 1998). This approach welcomes a vast array of methodological approaches. Scenario development as a use case was employed by Somé (2005) for validation purposes. It is for this reason that scenarios will be formulated by theoretically applying the TD artefact that will be derived from this research.

UCA is not a foreign concept to sustainability research, with evidence demonstrating it is widely applied but confronted with challenges associated with methodological rigour and comparability (Corcoran *et al.*, 2004). For this research, qualitative systems mapping is utilised since it enhances rigour and comparability with systematic, transparent protocols for integrating diverse knowledge concerning complex problems and as a means of supporting transdisciplinary communication (Hanger-Kopp *et al.*, 2024). Given that sustainability challenges are complex (Allen *et al.*, 2014), qualitative systems mapping is, indeed, appropriate. As a means of visualising complexity and informing intervention design (Pronk & Lee, 2024), qualitative systems mapping can cater for dependency and impact mapping. Dependency mapping is an introspective mapping approach to outline the interdependencies among components (Li *et al.*, 2012). Impact mapping is the converse, serving as an outward-thinking approach which aligns business goals during software development or projects (Adzic & Bisset, 2012).

To ensure comparability, some use-case analyses are measured against frameworks or metrics. España *et al.* (2010) are testaments of a framework-based comparison of use cases to a method evaluation framework. Similarly, Sabharwal *et al.* (2017) perform metric-based evaluations for a use case diagram complexity metric against a particular framework. Given that this research is housed with sustainability contexts for South Africa while aligned to ensuring a Sustainable Competitive Advantage, a similar approach is followed. For context and relevance, the SDGs, Africa Union 2063 Goals and Priorities will serve as impact mapping against metrics for Sustainability, while the VRIO framework and Nature Capital Protocol will serve as dependency mapping as a Nature-Resource based View (NRBV) lens. The inclusion of an IE or ES framework or taxonomy would be redundant given the classification and integration in the preceding DSR cycles. It is inherently part of the TD artefact.

Another appropriate technique within traditional ADR applications is that of participant observation. Participant observation occupies a well-established place within the action research tradition, particularly in its most widely cited cyclical formulation, in which the researcher moves iteratively through phases of diagnosing, action planning, action taking, evaluating, and specifying learning while remaining immersed in the setting under study. Baskerville and Wood-Harper (1998), in their classification of the diverse methodological forms that action research can take within information systems, identify participant observation as one of several legitimate variants alongside prototyping and soft systems methodology. They share that which unites these variants is the dual role of the researcher as both an active participant in organisational change and a producer of scientific knowledge about that change. As a data collection technique in its own right, participant observation is valued for its capacity to capture the tacit, situated, and often undocumented dimensions of practice. Kawulich (2005) and Musante and DeWalt (2010) emphasise that sustained immersion in a setting improves the quality of data collection and interpretation and enables the researcher to develop new research questions as understanding deepens, precisely because the method exposes routines, workarounds, and social dynamics that participants themselves may not think to report. This immersive, emergent quality is simultaneously the method's principal strength and its principal methodological burden, since the researcher's presence, interpretive lens, and evolving relationship with participants become inseparable from the data produced.

It is against this immersive, emergent backdrop that the comparative benefit of use case analysis becomes clear. Where participant observation yields rich but loosely bounded and interpretively demanding data, use case analysis offers a structured, artefact-oriented technique for capturing system requirements in an explicit, reviewable, and comparatively low-ambiguity form (Jacobson *et al.*, 1992). Each use case specifies a primary actor, a goal, and a bounded sequence of interaction steps, together with defined extensions for alternative or exceptional paths. This produces a discrete unit of documentation that can be validated against stakeholder expectations, revised, and traced through subsequent design and testing activity in a way that observational field notes cannot easily replicate. Since use cases are actor-and-goal-centred rather than setting-centred, they can be elicited, drafted, and reviewed relatively quickly once stakeholders are available, without requiring the sustained, long interaction participant observation typically demands to reach data saturation (Kawulich, 2005). This makes use case analysis considerably more time- and resource-efficient as a means of specifying what a system or process must do, and it produces the use case document itself as a standalone artefact. This can be directly reused as a design and verification reference, rather than requiring a further interpretive step to translate rich descriptive field notes into actionable system requirements.

The comparative advantage of use case analysis is, however, bounded by exactly the property that gives participant observation its value: use cases articulate what stakeholders can already state, or can be led to state, about intended system behaviour, whereas participant observation is capable of surfacing the undocumented, informal, and sometimes contradictory practices that stakeholders may not recognise, articulate, or wish to disclose in a structured elicitation setting (Kawulich, 2005; Musante & DeWalt, 2010). Within an action research cycle, this suggests the two techniques are best understood as addressing different points of vulnerability in organisational inquiry rather than as strict substitutes: participant observation is better suited to the diagnosing phase, where the researcher must first establish what is actually happening in a setting, including the gap between stated procedure and lived practice. In contrast, the use case analysis is better suited to the action planning phase, where that understanding must be converted into a specifiable, reviewable, and implementable description of desired system behaviour (Baskerville & Wood-Harper, 1998; Susman & Evered, 2023). The principal benefit of use case analysis over participant observation, then, is not that it replaces the depth of immersive fieldwork, but that it offers a far more efficient and directly actionable mechanism for converting an already-diagnosed problem into a specification that can be built against, tested, and traced after contextualisation.

3.8.2 Confirmatory Focus Group

A focus group is seen as a technique commonly applied in social sciences in a group setting to explore an idea or concept (Morgan, 1996). According to Monica Chiarini *et al.* (2010), artefacts for refinement and evaluation in design research can follow exploratory focus groups (EFGs) to propose improvements to the design or apply a field utility test in a confirmatory focus group (CFG). The purpose of the CFG in this research is to evaluate the relevance of the artefact in field use or confirm the preceding results (Monica Chiarini *et al.*, 2010).

Mazza and Berre (2007) developed a focus group methodology specifically for evaluating information visualisation techniques and tools. In their research, the advantages and disadvantages of focus groups are also explored. These are summarised in Table 10.

Table 10: Summary of advantages and disadvantages of focus groups adapted from Mazza and Berre (2007)

Advantages	Disadvantages
Qualitative data faster and more cost-effective than other methods	Small sizes limit generalisability and can create dependence amongst each other
Rich data obtained through direct interaction with opportunities for clarity in the evaluation	Dominant members may bias results
Respondents can engage with each other, creating collective ideas that could not have been generated otherwise	Analysis can become difficult with open-ended nature of responses
	A skilled and experienced moderator is often needed

The size of focus groups varies, but some research suggests between 6 and 12 people (Monica Chiarini *et al.*, 2010) or even 7 and 10 (Simon, 1999). However, Morgan (1996)

suggests between 4 and 12 people is preferable to avoid social loafing if too high, or high participation if too low (Monica Chiarini *et al.*, 2010). Tang and Davis (1995) identified various factors that also impact the size of the focus group. The main factor that influences the size is the aim of the study. Examples of other factors include the number of questions, the allotted time per question, the format of the focus group session (online or in-person) and the total duration of the session (Tang & Davis, 1995).

To prevent dominant members, participants will be capped at a maximum of two minutes to provide input one instance at a time. They are allowed to provide more than one response to a topic. Considering that open-ended questions make analysis difficult, only a few questions will be incorporated into the CFG. Although Schwarz (1994) believes a skilled moderator can manage interactions and emotions for a focused focus group, this research will have the researcher serve as the moderator. When research does not make use of moderators, it creates more organic discussions, makes participants feel constrained, extracts richer data and also aligns with findings that suggest moderators have little impact and that simpler structures in focus groups may be ideal (Schmidt & Hunter, 1978).

The use of focus groups does not need to occur in isolation. Morgan (1996) comments on the use of focus groups in combination with other methods. It was found that the most common combinations with focus groups were in-depth, individual interviews or surveys. A combination of focus groups and surveys contains primary and secondary applications (Morgan, 1993), but this research will not consider primary and secondary applications since they require sequential application. This research will simultaneously combine focus groups and surveys in one confirmatory focus group.

Similarly, O'Raghallaigh *et al.* (2012) make substantial efforts to report on how focus groups can be used to evaluate artefacts in design research. Their steps in organising a focus group in design research are. Numbered as follows:

1. Define the research problem and type of focus group - namely two: an exploratory focus group (EFG) and a confirmatory focus group (CFG). The type is reliant on the research goals or intent
2. Determining the number and duration of focus groups – the point at which the researcher suggests saturation has been reached
3. Determining the number and type of participants in each focus group session – identifying representative, insightful and motivated participants is pivotal. The focus group composition depends on the research problem, participant characteristics and solution being evaluated with as few as four and as many as twelve participants per group.
4. Identifying the moderator – based on required personality, nature and abilities, they should have a good understanding of the artefact being evaluated and able to present to the focus group
5. Identifying a questioning route – a focus group agenda for guidelines in the discussions and must be aligned with the research problem

The researcher will serve as the moderator in a confirmatory focus group by inviting the same sample used in the interviews. This thus identifies the focus group using preceding expertise within a TD context. Only one CFG group will be established. To avoid confirmation bias, open-ended questions are factored into this design as recommended by Schneider (2000).

The longer the duration of the focus group, the increased likelihood of fatigue and disengagement (Braun *et al.*, 2021). For the duration of the session, Mazza and Berre (2007) suggest that a session should last between 1 to 2 hours and explore 6 to 10 topics. In this study, the session will be scheduled for 1.5 hours with a 10-minute introduction to the session, followed by 1 hour and 15 minutes on the confirmatory focus group discussions and online survey statements in the form of polls. Five minutes will be used to conclude and round up the focus group, express words of thanks and end the recording.

The steps for organising focus groups in Design Science Research follow the guidelines modelled from various academics in the field (Gibbs, 1997; Monica Chiarini *et al.*, 2010; O'Raghallaigh *et al.*, 2012). These steps are presented in Table 11.

Table 11: Steps for organising a focus group in Design Science Research applied to the study

Step	Description	Application to study
Define research problem and type of focus group	The nature of the research problem must inform	The DSR artefact (framework) has not been validated in the relevance cycle of DSR. CFG is therefore selected. The research problem will be provided as context in the agenda of the CFG.
Determining the number and duration of the focus groups	The researcher must decide on these parameters that can best inform the number	The panel will comprise of one CFG for one hour. This abides with the literature review from Chapter 2 and in accordance with the research design from Chapter 3.
Determine the number and type of participants in each focus group	Representative, insightful and motivated participants should be selected with suggested bounds of between four and 12 per CFG	The same panel from the interviews (industrial engineers or environmental managers/practitioners with at least four years of experience) will be invited. Based on the response rate, the number of participants will be balanced with academic and industry representation with, at most ,10 individuals.
Identify the moderator	A moderator may be required to handle the complex and open-ended nature of focus groups	The researcher will serve as the moderator. This has been motivated in Chapters 2 and 3 under the dedicated CFG subsections.
Identify a questioning route	The agenda of the CFG should provide direction that is aligned with the research problem	Table 8 embodies the agenda with the use of survey statements to reduce open-ended responses

The structure of the confirmatory focus group uses the principles from O'Raghallaigh *et al.* (2012) and, Roopa (2021). The structure of the focus group conforms with the guidelines previously discussed, but follows an online format with an online survey component similar to Poliandri *et al.* (2023) as well as van der Linde and Roopa (2021). For the survey statements, a 5-point Likert scale will be used. As for the questions posed to the group, pseudo-anonymisation will be applied to transcripts from the recorded session. A summary of the intended questions or survey statements that will be evaluated is presented in Table 12.

Table 12: Confirmatory Focus Group Agenda

Topic	Question or survey statement	Question or online statement	Scale or question structure
Welcoming	Welcoming and briefing	4 minutes	N/A
Introduction	Online presentation with design logic, framework and intent of study discussed	10-minute presentation	N/A
Research problem	ST1. The knowledge of IE and environmental sustainability currently remains disconnected with organisations unable to successfully adopt environmental sustainability for a sustainable competitive advantage in South Africa.	Online survey statement (2 minutes)	5-point Likert scale
Framework relevance to problem	Q1. To what extent do you believe this framework addresses the aforementioned research problem?	Online discussion (10 minutes)	Open-ended
Framework's representation of IE	ST2. The framework demonstrates knowledge that is from IE	Online survey statement (2 minutes)	5-point Likert scale
Framework's representation of IE	ST3. The framework demonstrates knowledge that is from environmental sustainability	Online survey statement (2 minutes)	5-point Likert scale
Knowledge components structure	ST4. The framework demonstrates cascading and aligns with the business execution levels	Online survey statement (2 minutes)	5-point Likert scale

Topic	Question statement or survey	Question or online statement	Scale or question structure
	Q2. What is your opinion regarding the classification of the cascading effect from the framework?	Online discussion (10 minutes)	Open-ended
Framework's representation of IE and ES for SCA	ST5. The framework demonstrates mechanisms to ensure a sustainable competitive advantage in South Africa	Online survey statement (2 minutes)	5-point Likert scale
Implications and relevance of framework (O'Raghallaigh <i>et al.</i> , 2012)	ST6. The framework addresses the research problem	Online survey statement (2 minutes)	5-point Likert scale
	Q3. Why do you believe this framework can promote environmental sustainability and ensure a sustainable competitive advantage?	Online discussion (10 minutes)	Open-ended
Method of improving framework (O'Raghallaigh <i>et al.</i> , 2012)	Q4. What suggestions would you make to improve the framework?	Online discussion (10 minutes)	Open-ended

Although six topics are recommended in CFGs, 10 have been selected for this study, given the quick response rate the survey statements will yield. The online survey statements will be presented using an online Google Form to create a poll during an MS Teams meeting with participants. The results will entail individual scores; the average and the standard deviation.

A 5-point Likert scale will be used to evaluate the survey statements. The survey statements test the design requirements and ability of the framework to correctly use IE knowledge to ensure environmental sustainability for South Africa, for a sustainable competitive advantage. An average of more than 3.75 will be used to indicate that consensus has been reached on a five-point Likert scale (Rahem & Darrah, 2018), with the following value descriptions:

- a) 1: Major disagreement
- b) 2: Minor disagreement
- c) 3: Undecided
- d) 4: Minor agreement
- e) 5: Major agreement

Participants will have the opportunity to provide feedback in the open-ended questions. Thematic analysis will be used to analyse the discussions tied to questions. In a similar approach to Siriram (2023), atlas.ti will be used to analyse focus group data and configure and report on theme contributions. Themes pre-emptively selected for this study are: enablers, barriers, improvements, future research, limitations and validation. These themes will be used to create discussion points within each respective question posed during the focus group. For the Likert-scale survey statements, descriptive statistics in terms of mean and standard deviation will be used for interpretation. Sample characteristics will not be gauged to ensure participant identities are protected

3.8.3 Verification and validation of TD artefact

Haskins (2016) mentions that verification entails a process used to develop evidence that a design satisfies set requirements. Complementary to this, validation evaluates the appropriateness of interpretations based on assessment results. In this research, verification and validation occur across the use case analysis and confirmatory focus group. The use case analysis will verify the solution streams across the various assessment metrics, whereas the confirmatory focus group evaluates (by means of a survey feature) the impact of the TD artefact within the South African domain using subject matter experts. Collectively, the design requirements are tested via the survey, whereas impact and relevance are evaluated intrinsically via dependency mapping and extrinsically using impact mapping. Transdisciplinary representation in the CFG is warranted by the inclusion of academic and non-academic stakeholders which stem outside more than one discipline Bracken *et al.* (2015).

3.9 Limitations

Several shortcomings emerge from the research design when considering the stages in the study. In the first part of the research, the SLR is restricted to publications available up to 2021 and limited to English-language sources. This creates potential publication and language bias. This also means that more recent IE and ES knowledge is not reflected in the framework. The interview data is safeguarded by saturation principles; however, the size of the population known to the research introduces network bias. The research has a cross-sectional time horizon which makes it more challenging to track how the relationship between environmental sustainability and IE changes over time. The study is unable to capture long-term changes in sustainability practices, organisational adoption, or evolving knowledge integration since the systematic literature review, interviews, use case analysis and confirmatory focus group are conducted at specific periods in time.

The Design Science Research (DSR) strategy emphasizes the development and assessment of a conceptual artefact rather than its implementation in actual organisational settings. The artefact undergoes evaluation via use case analysis and expert validation, yet it is not subjected to comprehensive organisational deployment testing. This may make it harder to understand problems with putting things into practice, resistance from the organisation, or results in operational performance. The CFG draws from an earlier interview sample which created informed evaluation while introducing confirmation bias catered for by the use case analysis. Even though the intended findings could hold relevance for other developing countries, the contextual nature of the TD artefact may limit its transferability without adaptation to different contexts. These contexts include institutional, political, economic, social or environmental dynamics which are country specific.

Ultimately, this research boasts conceptual integration of IE and environmental sustainability knowledge instead of broad empirical generalisation.

3.10 Ethical considerations

This study will enforce the following ethical considerations as advised by De Vos *et al.* (2011):

- **Voluntary participation** – The researcher will obtain voluntary participation via an independent researcher who will make first contact for Stage 2. In this way, the researcher is unable to coerce any participants. In conjunction, participants will be able to withdraw from the research at any time. The same applies to Stage 4.
- **Informed consent** – The researchers will provide prospective participants with an informed consent form. For the interviews, this will be prior to completing an online Google Form in which the survey will be designed.
- **Non-deception of subjects and/or respondents** – The researcher will not reserve and distort information or mislead participants on specific context related to the research.
- **Non-violation of privacy / anonymity / confidentiality** — The researcher will respect the privacy of all participants at all times during the study. Furthermore, the researcher will not publish any confidential information provided by the participants. The researcher will password-protect all data for five years.
- **Publication of findings** – The researcher will document all the findings throughout the thesis and in each research publication proposed. All relevant findings will be conveyed such that no information is misrepresented or altered / adjusted.
- **Ethics committees** – The researcher will ensure that permission is obtained from the North-West University Engineering Research Ethics Committee (NWU-ENG-REC). All processes and procedures will be carefully followed.

On 27 March 2024, the NWU-ENG-REC cleared this study as a low-risk study, assigning it the ethics number NWU-00235-23-A3. The ethics approval letter can be found in Appendix B.

3.11 Chapter summary

The study employs a constructivist philosophy and a deductive, multi-method approach within a cross-sectional time horizon, guided by the research onion framework and carried out through Design Science Research (DSR). In accordance with the DSR cycles, the design takes place in four stages: a systematic literature review and thematic analysis to identify knowledge components; interviews with South African industrial engineers and environmental practitioners to contextualize these insights; the creation of a transdisciplinary artefact using the Abstract–Contextualize–Design methodology backed by Pareto-weighted Thematic Analysis; and, finally, an evaluation of the artefact through use case analysis and a confirmatory focus group. This structured design integrates qualitative and limited quantitative techniques. It also acknowledges methodological limitations and adheres to established ethical research practices.

Chapter 4

4 Exploring Industrial Engineering Knowledge and Environmental Sustainability

This chapter serves as the first research output **published** in the Journal of **Sustainability** (Q1).

Abstract: This research identifies the relationship between industrial engineering and environmental sustainability knowledge components. A combination of a Systematic Literature Review (SLR) and Applied Thematic Analysis (ATA) is employed in this research to uncover pertinent literature associated with the purpose of this research. Whilst various forms of strategies, theories, methods and practices were uncovered in each of the knowledge components, only a few were overlapping. These overlapping components include green supply chain operations, circular economy, and technology management. This study is the first in a series of studies contextualising industrial engineering knowledge in terms of its applicability to environmental sustainability. These results reveal concepts from industrial engineering and environmental sustainability knowledge components that can be used to systematically design methodologies or practically implement them in an industry or organisation. Methods and practices were a dedicated theme in the analysis which can be used by practitioners. A circle packing diagram is crafted using the IISE Body of Knowledge as a means of categorisation. This study considered IE as a catalyst in creating new forms of transdisciplinary knowledge areas. It also considers how IE knowledge can contribute to environmental challenges.

Keywords: Industrial Engineering; Environmental sustainability; Transdisciplinary knowledge; Systematic Literature Review; Applied Thematic Analysis

Doi: <https://doi.org/10.3390/su16177392>

Introduction: Chapter 4 reproduces the first research output of the thesis, published in the Q1 journal *Sustainability*. It opens the thesis's empirical evaluation by asking a foundational question: to what extent does the existing literature already connect Industrial Engineering (IE) knowledge to environmental sustainability (ES) knowledge? The chapter situates this question against the backdrop of successive industrial revolutions, each of which has delivered societal and economic gains while simultaneously imposing an environmental burden through urbanisation, industrialisation, resource consumption and pollution, particularly in developing and underdeveloped countries. IE is introduced as a multidisciplinary profession whose subconscious solution space, comprising theories, strategies, tools and methods, is applicable across almost any sector, giving it a plausible claim to a leadership role in addressing environmental degradation. The chapter traces the evolution of sustainability thinking through the "Mickey Mouse" siloed model, the triple bottom line, and the embedded bullseye model, before narrowing its focus to environmental sustainability specifically, defined as the protection of the raw material sources that sustain both anthropogenic activity and global life-support systems.

The chapter then interrogates the IE profession's own knowledge architecture. Two dominant IE taxonomies are examined, namely the IISE Body of Knowledge (fourteen knowledge areas) and Salvendy's domains of industrial engineering. Despite the existence of environmental law and clean manufacturing content within general IE handbooks, the chapter observes that neither canonical taxonomy formally associates environmental sustainability with a dedicated IE knowledge domain or application area. This absence is framed as a structural blind spot: IE possesses the productivity-oriented tools that could plausibly serve environmental ends, yet the profession's own classification systems do not name or organise this capability. The introduction closes by positioning transdisciplinary (TD) knowledge, and specifically industrial ecology as a cognate TD field, as the appropriate lens through which this gap should be closed, since sustainability problems are argued in the literature to require new forms of knowledge production that exceed what any single discipline can offer alone.

Relevant research component: The overarching research question driving Chapter 4 is stated explicitly: "What is the relationship between industrial engineering knowledge and environmental sustainability knowledge?" This single question dictates the entire design. The stated research aim is to conduct a systematic literature review (SLR) that establishes and categorises the applicable forms of strategy, theory, methods and practice that embody both IE knowledge and ES knowledge. Three supporting objectives operationalise this aim: first, to identify the most prominent forms of IE knowledge that promote environmental sustainability; second, to determine the most prominent forms of IE and ES strategies, theories, methods and practices; and third, to identify the specific knowledge components that overlap between the two domains. Framed this way, the chapter's ambition is deliberately modest and literature-bound. It does not yet attempt to engage practitioners, design an artefact, or validate a framework. Its purpose is to establish, with methodological rigour, whether and where a genuine intersection between

IE and ES exists in the published literature, thereby creating the evidentiary foundation on which the rest of the thesis is built.

Methodology: Chapter 4 combines a systematic literature review (SLR) with Applied Thematic Analysis (ATA). The SLR follows a ten-step process (planning, conducting, and documenting the review) adapted from Albliwi et al. (2014) and aligned with the PRISMA 2020 statement and its PRISMA-S extension for search reporting. A structured search protocol was designed around the Boolean search string "Industrial Engineering" AND "Environmental Sustainability", executed across six databases: Science Direct, Scopus, IEEE Explore, Web of Science, EBSCOhost, and Emerald Insight, with no lower time bound and a cut-off of October 2023. This search returned 95 records, which were reduced to 89 after de-duplication, then to 31 following title-and-abstract screening, and finally to 23 papers after full-text eligibility screening, with the entire filtering process visualised using a PRISMA flow diagram and cross-checked by two researchers to reduce bias.

The 23 retained papers were then subjected to thematic analysis in atlas.ti (version 24.1.1), coded into five theme sets, namely strategy, theory, methods and practices for IE, and the same four categories for ES, which were deliberately mapped onto the three-tier business execution model (strategic, tactical, operational). Code co-occurrence was calculated to quantify overlap between IE and ES codes, and the results were further visualised using a network diagram and, distinctively, a circle-packing diagram that superimposes the extracted knowledge components onto the IISE Body of Knowledge's fourteen areas, with an additional "unspecified" category created for components that did not conform to any IISE area. This combination of a reproducible, PRISMA-compliant SLR with a structured, code-density-driven thematic analysis gives the chapter's findings both literature coverage and fine-grained categorisation. It establishes a methodological precedent, the SLR thematic-analysis pairing, that recurs, in modified form, throughout the rest of the thesis.

Core findings: The thematic analysis revealed that IE and ES knowledge remain, for the most part, informal within the literature. From the code intersections tested, only three knowledge components showed genuine overlap between IE and ES. These were green supply chain operations, circular economy, and technology management. The strongest overlap band overall existed between practices and theories, with seven instances of density overlap, while several IE-ES code pairings returned a zero count, empirically confirming the fragmentation the chapter set out to test for. Distinct strategy tables were produced for IE (including Industry 4.0, technology leapfrogging, supply chain management, and business strategy and profitability) and for ES (dominated by circular economy and sharing principles, resource conservation, carbon-footprint reduction, and the planetary boundaries framework). Interestingly, circular economy emerged as the single most popular ES strategy identified in the corpus. A parallel exercise for theory surfaced Lean, analytical/mathematical modelling, and supply chain sustainability as prominent IE theories, set against life cycle analysis, industrial ecology, and distributive justice theories on the ES side. Methods and practices proved too fragmented for

tabulation and were instead discussed narratively, spanning ISO 9000/14000 standards, life cycle analysis, environmental accounting, energy analysis, and eco-labelling.

The circle-packing visualisation, built on the IISE Body of Knowledge, showed a reasonably even spread of ES-related knowledge components across the fourteen IE knowledge areas, but also exposed clear imbalances: the Safety knowledge area was almost entirely unpopulated by ES content, Engineering Economic Analysis returned only IE-side components with no ES equivalent, and thirteen knowledge components could not be mapped to any IISE category at all and had to be housed in an "unspecified" residual class. The discussion interprets these findings through the Quadruple Helix innovation model (academia, industry, government, society), arguing that the results carry direct implications for engineering curricula, industry implementation and policy formulation, for example through the enforcement of ISO and ESG reporting standards. The chapter closes by concluding that IE can act as a catalyst for new transdisciplinary knowledge, but that its current body-of-knowledge architecture does not yet formally accommodate environmental sustainability, and it flags Lean and Green and industrial ecology as the most promising existing hybrid constructs on which to build.

Reflections: Chapter 4 is a careful, conservative piece of scholarship which makes no artefact-development claims and confines itself to establishing, through a defensible and reproducible method, that a research gap genuinely exists rather than being merely asserted. In this way, it complements the identified research problem. Its principal strength is precisely this restraint; the PRISMA-compliant SLR and the dual-researcher review process give the lack of formalisation finding real evidentiary weight, which matters because the rest of the thesis is constructed on the premise that this fragmentation is real and worth resolving. The circle-packing diagram is a particularly effective contribution in this regard, since it does not merely assert a gap in the abstract but locates it precisely within the established professional taxonomy (the IISE Body of Knowledge), thus making the gap legible to an IE practitioner audience in a way a purely narrative literature review would not.

The chapter's self-acknowledged limitations are equally instructive for the thesis as a whole. Its findings are explicitly generic, unspecific to any industry, sector or country, and derived entirely from secondary literature rather than practitioner input. This is not presented as a flaw so much as a deliberate scoping decision, but it does mean that Chapter 4's conclusions are, by its own admission, insufficient to inform real-world implementation without further contextualisation. This limitation is significant for understanding the thesis's overall research design, since it explains why an SLR alone was judged insufficient to satisfy the thesis's aim, and why a second, empirically grounded study became necessary.

Inter-relationships across other chapters: The central finding, that IE and ES knowledge are only thinly connected in the literature, directly motivates the problem statement articulated in Chapter 1 and expanded upon in Chapter 2's literature review. Both of these draw on the same taxonomic gap, the absence of environmental sustainability from the IISE Body of Knowledge and Salvendy's domains identified here. Methodologically,

Chapter 4 establishes the SLR, as well as the thematic analysis approach, the three-tier strategic/tactical/operational classification of knowledge components, and the atlas.ti coding protocol that Chapter 5 explicitly imports and extends into a qualitative interview study. This is what the TD artefact in Chapter 7 re-uses as one of its two raw data sources. The 23 papers and their associated codes generated in Chapter 4 are, in fact, explicitly re-ingested as literature-based input into Chapter 7's Pareto-Weighted Thematic Analysis. Due to this, the finds from Chapter 4 are not merely conceptually antecedent to later chapters but are structurally embedded within the final TD artefact. The lighthouse model (Chapter 6) and use case analysis (Chapter 9) both inherit, more indirectly, the same foundational premise that IE knowledge can be systematically catalogued and mapped onto sustainability outcomes, a premise Chapter 4 is the first to test and substantiate empirically.

Review

Exploring Industrial Engineering Knowledge and Environmental Sustainability

Meelan Roopa ^{1,*} , Rajenlall Siriram ²  and Rojanette Coetzee ² 

¹ Department of Industrial Engineering, Stellenbosch University, Stellenbosch 7602, South Africa

² School of Industrial Engineering, North-West University, Potchefstroom 2531, South Africa; raj.siriram@nwu.ac.za (R.S.); rojanette.coetzee@nwu.ac.za (R.C.)

* Correspondence: meelanroopa@sun.ac.za

Abstract: This research identifies the relationship between industrial engineering and environmental sustainability knowledge components. A combination of a systematic literature review (SLR) and applied thematic analysis (ATA) is employed to uncover the pertinent literature associated with the purpose of this research. Whilst various forms of strategies, theories, methods, and practices were uncovered in each of the knowledge components, only a few were overlapping. These overlapping components include green supply chain operations, circular economy, and technology management. This study is the first in a series of studies contextualising industrial engineering knowledge in terms of its applicability to environmental sustainability. These results reveal concepts from industrial engineering and environmental sustainability knowledge components that can be used to systematically design methodologies or practically implement them in an industry or organisation. Methods and practices were a dedicated theme in the analysis, and these can be used by practitioners. A circle packing diagram is crafted using the IISE Body of Knowledge as a means of categorisation. This study considered industrial engineering as a catalyst in creating new forms of transdisciplinary knowledge areas. It also considers how industrial engineering knowledge can contribute to meeting environmental challenges.

Keywords: industrial engineering; environmental sustainability; transdisciplinary knowledge; systematic literature review; applied thematic analysis



Citation: Roopa, M.; Siriram, R.; Coetzee, R. Exploring Industrial Engineering Knowledge and Environmental Sustainability. *Sustainability* **2024**, *16*, 7392. <https://doi.org/10.3390/su16177392>

Academic Editor: Irene Petrosillo

Received: 1 July 2024

Revised: 14 August 2024

Accepted: 20 August 2024

Published: 27 August 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Each industrial revolution has ensured progression through developmental changes that render societal gains. These societal gains are experienced in various sectors, ensuring economic growth and prosperity through technological advances. However, each revolution has also imposed an environmental burden which cannot go unnoticed. Urbanisation and industrialisation lead to high resource consumption and environmental pollution experienced in underdeveloped and developing countries [1,2]. This has been linked with environmental regulations which offset environmental degradation in African countries [3].

Industrial engineering finds itself at the forefront of innovation with a subconscious solution space comprising various theories, strategies, tools, and methods that apply to multidisciplinary environments and numerous sectors. The nature of these solutions appeals to a broad range of problems, such is the value and contribution of this discipline. The environmental challenges experienced by developing countries are extensive, ranging from waste generation, water and energy consumption, greenhouse gas emissions, pollution, and sanitation [4–6].

Sustainability has emerged in response to the growing advances made in the world. It comprises environmental, social, and economic pillars. These are first considered siloed (“Mickey Mouse” model), interrelated (triple bottom line model), and finally embedded in a bullseye model through improved understanding over time [7,8]. An approach used

to facilitate the balance of societal needs and environmental preservation is through environmental sustainability. Environmental sustainability (ES) is concerned with improving social welfare by protecting the sources of raw materials used in anthropogenic activities so as to sustain global life-support systems [9,10]. ES is often associated with transformations that meet the needs of current and future generations without compromising the health of ecosystems [11,12]. Environmental sustainability in this research will embody various strategies, theories, and methods. ES has the potential to enable socio-economic systems to function well and add value across environmental, social, and economic boundaries.

The industrial engineering (IE) discipline is a growing field that continues to apply multidisciplinary knowledge to solve complex problems. Complex problems are believed to be ill-defined with no clear problem definition and goal state [13]. The IE discipline designs, improves, and implements integrated systems comprising people, materials, energy, equipment, and information [14]. The Institute of Industrial and Systems Engineers defines industrial engineering as follows [15]:

“Industrial Engineering is concerned with the design, improvement and installation of integrated systems of people, material, information, equipment and energy. It draws upon specialised knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems”.

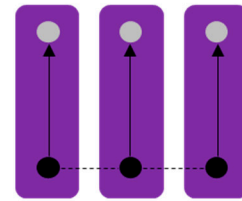
An industrial engineer is someone who can master various knowledge domains in order to creatively define, design, and refine solutions that maximise and balance value [16]. According to the resource-based theory, value is defined as an enabler for meeting customer needs and is associated with strengths within a firm [17,18]. The origins of the IE profession stem from industrial thinking from the industrial revolutions [19,20]. The profession has been recognised for its ability to improve the productivity, profitability, and efficacy of organizations using its versatile skillset and knowledge [21]. These skills and knowledge have a wide range of applications, from supply chain management to Industry 4.0 adoption.

The knowledge of the industrial engineering profession offers itself as a remedy to the negative impact associated with each industrial revolution. Knowledge is cultivated, diversified, and disseminated in the literature. Industrial engineering knowledge has been classified according to various knowledge domains and application areas that are multidisciplinary in nature. Despite the inclusion of chapters discussing environmental law and clean manufacturing in the Handbook of Industrial Engineering [22], environmental sustainability has not been associated with a specific industrial engineering knowledge domain or application area. The Institute of Industrial and Systems Engineers (IISE) [23] details the industrial engineering body of knowledge as a composition of 14 knowledge areas. Another taxonomy for IE knowledge is the domains of industrial engineering (Salvendy [22]). However, the IE profession must be more focused on sustainability to remain relevant [21,24]. Furthermore, this profession holds the potential to provide a nuanced manner of addressing the environmental degradation imposed by industrial activities.

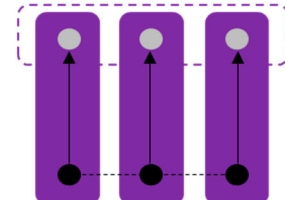
While this body of knowledge may seem promising, its structure prevents it from making systemic improvements to environmental concerns. According to Lang, et al. [25], sustainability issues require new ways of knowledge production and decision making, stressing the need for transdisciplinary research. Transdisciplinary research combines interdisciplinarity with a participatory approach by involving academics from unrelated disciplines and non-academics to create new knowledge and theories addressing complex research questions [26,27]. Figure 1 provides an overview of the evolution of research strategies shifting from disciplinary to transdisciplinary in nature.

Disciplinary

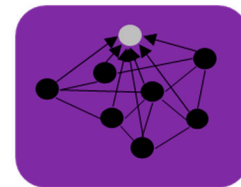
- Within one academic discipline
- Disciplinary goal setting
- Siloed between disciplines
- Development of new disciplinary knowledge and theory

**Multidisciplinarity**

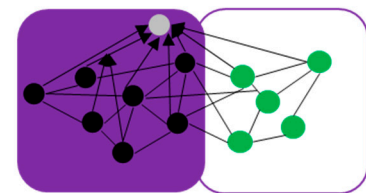
- Multiple disciplines
- Multi-disciplinary goal setting
- Loose cooperation of disciplines during knowledge exchange
- Disciplinary theory development

**Interdisciplinarity**

- Crosses disciplinary boundaries
- Common goal setting
- Integration of disciplines
- Development of integrated knowledge and theory

**Transdisciplinarity**

- Crosses disciplinary and scientific/academic boundaries
- Common goal setting
- Integration of disciplines and non-academics
- Development of integrated knowledge and theory among science and society

**Legend**

- | | | | |
|------------------------------|--|-------------------------------|--|
| • Discipline | | • Thematic umbrella | |
| • Non-academics | | • Academic knowledge body | |
| • Goal of a research project | | • Non-academic knowledge body | |
| • Movement towards goal | | | |
| • Cooperation | | | |
| • Integration | | | |

Figure 1. Transdisciplinary, interdisciplinary, multidisciplinary, and disciplinary overview redrawn from Tress et al. (2005) [26].

Although the industrial engineering profession is considered multidisciplinary, efforts to associate its theory with environmental sustainability are best explored by acknowledging research that would be transdisciplinary. An iconic transdisciplinary field of research is industrial ecology. This field focuses on the industrial metabolism focused on by industrial engineers, and environmental metabolism that concerns environmental managers [28,29]. An industrial system is perceived as an ecosystem that balances material, energy, and information flows [30,31]. Furthermore, it is also encouraged that engineers include interdisciplinary knowledge beyond what is strictly associated with the engineering domain [32]. Whilst giving recognition to the field of industrial ecology and its advances, the focus of this study will be to further industrial engineering knowledge and its association with environmental sustainability.

Despite the productivity achievements owed to the industrial engineering profession, it is yet to make noteworthy strides with regard to sustainable development [24]. There is research identifying that industrial engineering can contribute to the knowledge era [8]. In the knowledge era, traditional engines of wealth creation are eclipsed by the importance of intellect. More specifically, the industrial engineering knowledge area has made contributions by utilising Bayesian statistics for comparing energy efficiency gains as a proclaimed IE tool [24]. Lean and Green is also a hybrid knowledge domain that combines a well-established Lean theory domain focused on productivity, with environmental (green) considerations [33,34]. Notwithstanding these valuable insights from these researchers, there is limited research specifically focused on environmental sustainability practices as an initial starting point to ensure synergy between industrial engineering knowledge and environmental sustainability.

For the profession to remain relevant, this field of study must be explored. The industrial engineer will redefine environmental issues and sustainability [21]. This research takes this unique stride by investigating the degree to which environmental sustainability knowledge can be linked with industrial engineering knowledge in its all-encompassing fashion.

2. Research Question, Aim, and Objectives

The over-arching research question is as follows: What is the relationship between industrial engineering knowledge and environmental sustainability knowledge?

The aim of this research is to conduct a systematic literature review to establish and categorise the applicable forms of strategy, theory, methods, and practices that embody industrial engineering knowledge and environmental sustainability.

This is further segmented into the following research objectives:

1. Identify which are the most prominent forms of industrial engineering knowledge that promote environmental sustainability.
2. Determine the most prominent forms of industrial engineering and environmental sustainability strategies, theories, methods, and practices.
3. Identify overlapping knowledge components associated with industrial engineering and environmental sustainability.

3. Research Method

To achieve this aim, a systematic literature review (SLR) and thematic analysis have been performed. An SLR is a rigorous method that can be used to identify, evaluate, and synthesise a large body of literature in a reproducible fashion [35]. In contrast, a thematic analysis is used to perform a textual analysis of the literature filtered from the SLR into defined themes that are coded using the atlas.ti software platform, version 24.1.1. It is commonly used to code and annotate bodies of unstructured data. This caters for textual data categorisation for qualitative analysis. In a similar approach followed by Mangaroo-Pillay, et al. [36], the SLR comprises the following steps (illustrated in Figure 2), which are cast in respective phases.

Each step from this method has been acknowledged using the subsections that follow. The technical detail and result from each step are elucidated.

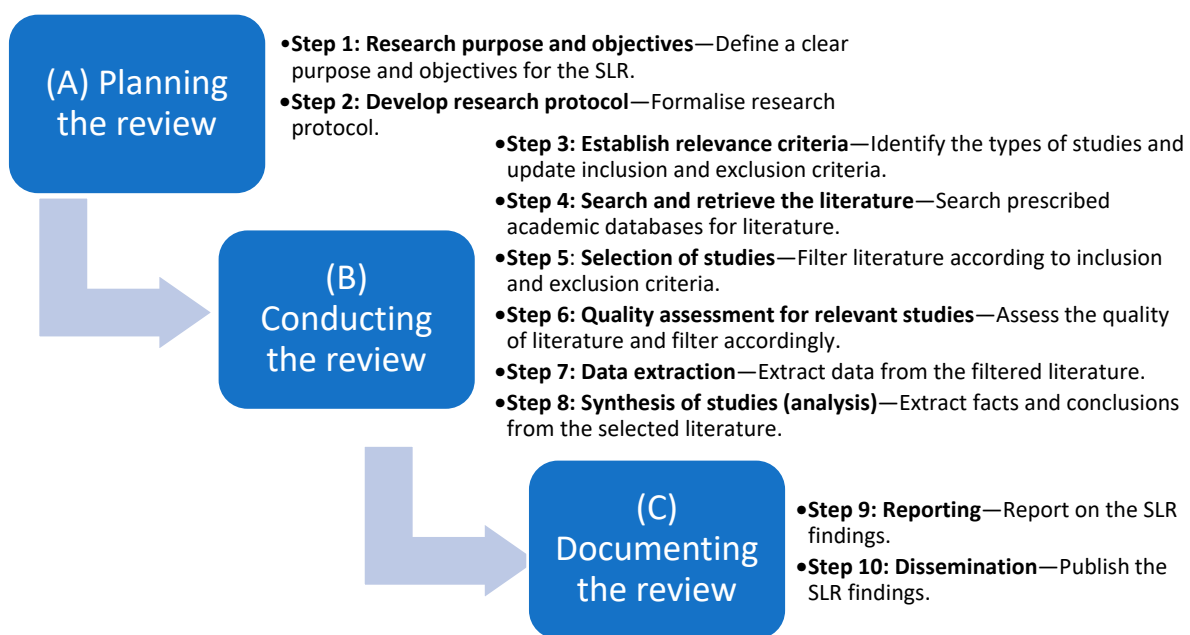


Figure 2. SLR process from Albliwi et al. (2014) [37].

4. Results and Findings

4.1. Step 1: Research Purpose and Objective

The aim of this research is to establish and categorise applicable forms of strategy, theory, methods, and practices that embody industrial engineering knowledge and environmental sustainability knowledge. The objectives are to (1) identify the prominent forms of industrial engineering knowledge that promote environmental sustainability and (2) synthesise the forms of industrial engineering and environmental sustainability strategies, theory, methods, and practice.

4.2. Step 2: Develop Research Protocol

To achieve the aim and objectives of this research, the research protocol was designed as in Table 1. Each search component, specification, and rationale are clearly detailed.

Table 1. SLR search protocol.

Search Component	Specifications	Rationale
Keywords	Industrial Engineering, Environmental Sustainability.	Key terms relevant to the purposes of this study.
Platforms	Science Direct, Scopus, IEEE Explore, Web of Science, EBSCO host, Emerald Insight.	Reputable academic databases accessible to the researcher.
Search strategy	“Industrial Engineering” AND “Environmental Sustainability”.	Boolean operator for the union of the content. Wildcards are not considered.
Time frame	No lower bound, until October 2023.	Structured so as to unveil all available literature.
Inclusion criteria	Publications discussing theory, concepts, methods, strategies, and techniques that achieve or promote environmental sustainability.	Screen publications to conform with the scope of the study.
Exclusion criteria	Publications that are not in English, undergoing review. Curriculum design papers.	Protect the academic integrity and ability to analyse the research publications according to the aim of this study.
Quality assessment criteria	Remove all duplicates and filter according to papers relevant to the research aim.	Filter literature according to aspects beyond those in the inclusion and exclusion criteria.

It is also important to note that various databases were used within EbscoHost: Academic Search Complete, Applied Science and Technology, Business Source Complete, EconLit, E-Journal, Environment Complete, Greenfile, and Water & Oceans Worldwide.

4.3. Step 3: Establish Relevance Criteria

Through an iterative process of evaluating the cumulated search results and relevance of each topic, the inclusion and exclusion criteria were refined and are presented in Table 1.

4.4. Steps 4 to 6: Search, Selection, and Quality Assessment of the Literature

Following the aim of the research, only the literature relating to industrial engineering and environmental sustainability was considered to gain an understanding of this focused research area. The search strategy considered the abstracts of the initial set of reputable publications. The exceptions to this were Science Direct and Scopus, and their functionality facilitated collective searches on the title, abstract, and keyword. For the information sources and methods, a multi-database searching approach was employed in which no study registries were included. Online resources were accessed and subjected to abstract and title screening, followed by a full-text reading. No citation searching was adopted in the search strategy.

During the search and selection process, an initial cumulated literature search result of 95 publications was obtained. The results from each database were imported into an Excel file that was used to screen the data. CSV exports and manual copy and paste functionalities were used on the various databases to populate the aforementioned spreadsheet. The six duplicated research papers were first removed before title and abstract screening for relevance according to the prescribed eligibility criteria. The eligibility criteria were a product of the inclusion and exclusion criteria that removed certain forms of the literature as part of a rigorous synthesis method. After removing 58 publications, 31 were subjected to full-text reading. Eight publications were removed from this sample since they did not meet the eligibility criteria. Many of these publications were excluded since they were housed within engineering education or belonged to other engineering disciplines. The full search strategy and search filters are provided in Table 2, accompanied by the total records with deduplications removed.

Table 2. SLR search string strategies for the identification of relevant studies.

Search Database	Search String	Results
Science Direct	"Industrial Engineering" AND "Environmental sustainability"	1
Scopus	(TITLE-ABS-KEY ("Industrial Engineering") AND TITLE-ABS-KEY ("Environmental sustainability"))	37
IEEE Explore	("Abstract":Industrial Engineering) AND ("Abstract":Environmental sustainability)	20
Web of Science	"Industrial Engineering" (Abstract) and "Environmental sustainability" (Abstract)	3
EbscoHost	AB Industrial Engineering AND AB environmental sustainability	30
Emerald Insight	abstract:"Industrial Engineering" AND (abstract:"Environmental sustainability")	4

The PRISMA statement 2020 can be incorporated since this study serves as an original systematic literature review and may serve as the underpinning approach used to identify, select, appraise and synthesise studies [38]. More recently, the work by Rethlefsen, et al. [39] provides an extension to the PRISMA-S statement, which contains a more current checklist. A combination of these two PRISMA checklists has been employed in this study.

To reduce the study's risk of bias, the filtering and results were reviewed by two researchers. This systematic process is visualised in Figure 3 using the standard PRISMA approach by detailing the manual filtering between the cumulated results from the initial search and the final set of publications subjected to thematic analysis.

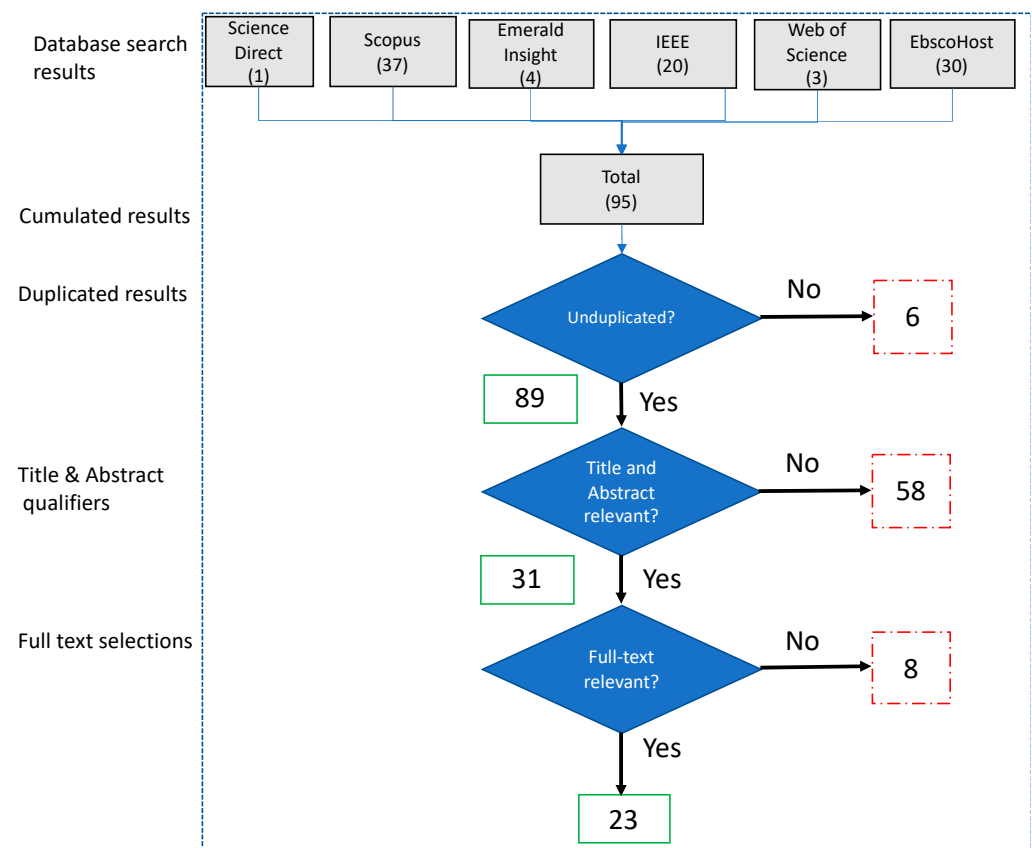


Figure 3. SLR filtering process.

The remaining 23 papers were subjected to thematic analysis using atlas.ti, discussed further in Section 4.5. The filtered publications were further categorised according to journal, year, and novelty. A summary of these papers is detailed in Table 3.

Table 3. SLR literature selection.

#	Author(s) and Year	Title	Year	Novelty
1	Djassemi [40]	A computer-based approach to material and process selection using sustainability and ecological criteria	2009	In a holistic computer-based approach, material and process selection is performed in accordance with sustainability and ecological criteria.
2	Naidu, et al. [41]	A methodology for evaluation and selection of nanoparticle manufacturing processes based on sustainability metrics	2008	An evaluation method that focuses on sustainability metrics ranging from economic, environmental, and sociological dimensions. Three nanoparticle manufacturing processes are evaluated.
3	Luque, et al. [42]	ADAPTS: An Intelligent Sustainable Conceptual Framework for Engineering Projects	2020	A description of the ADAPTS framework that includes the application, data, approach, tool, and sensing dimensions used to improve environmental sustainability of an olive oil manufacturing plant.
4	Jing, et al. [43]	Assessments on energy and greenhouse gas emissions of internal combustion engine automobiles and electric automobiles in the USA	2020	Integrated analysis of GHG emissions and energy in the industrial area of automobile engineering in the USA.
5	Helbig, et al. [44]	Benefits of resource strategy for sustainable materials research and development	2017	A framework proposed to reduce supply risk and enhance environmental sustainability taking into account basic research, technical development, application, and re-phase across a product life cycle
6	Hazen, et al. [45]	Big data and predictive analytics for supply chain sustainability: A theory-driven research agenda	2016	The paper proposes a research agenda for using big data and predictive analytics to improve supply chain sustainability by reviewing eight theories.

Table 3. Cont.

#	Author(s) and Year	Title	Year	Novelty
7	Tagliari, et al. [46]	Developing a specific structured procedure to assess sustainability performance in manufacturing processes	2020	A structured procedure to assess sustainability performance in manufacturing processes by taking into account the environmental, social, and economic dimensions of sustainability.
8	Dangelico, et al. [47]	Developing sustainable new products in the textile and upholstered furniture industries: Role of external integrative capabilities	2013	Proposes a new framework for understanding the role of external integrative capabilities in sustainable green product development.
9	Papoutsis and Sodhi [48]	Does disclosure in sustainability reports indicate actual sustainability performance?	2020	The research suggests that disclosure in sustainability reports can be a useful indicator of actual (realised) sustainability performance.
10	Ryberg, et al. [49]	Downscaling the planetary boundaries in absolute environmental sustainability assessments—A review	2020	The paper provides a comprehensive review of methods for downscaling planetary boundaries in absolute environmental sustainability assessments (AESAs).
11	Singh, et al. [50]	Environmental impact assessment of different design schemes of an industrial ecosystem	2007	An LCA environmental assessment impact of industrial ecosystems.
12	Harland, et al. [51]	Environmental sustainability in the semiconductor industry	2008	A framework to address environmental sustainability challenges of the semiconductor industry is presented.
13	Seifi [24]	Governance and Socially Responsible Energy Consumption	2013	A discussion on the links between industrial engineering and environmental sustainability while using Bayes Theorem as a method of analysis to compare energy consumption.
14	Ben-Zvi-Assaraf, et al. [32]	Harnessing the Environmental Professional Expertise of Engineering Students-The Course: ‘Environmental Management Systems in the Industry’	2010	The study explores their perception of industrial–environmental issues.
15	Singh and Lou [52]	Hierarchical pareto optimisation for the sustainable development of industrial ecosystems	2006	The paper proposes a novel methodology for improving the sustainable development of industrial ecosystems (IEs) by using hierarchical Pareto optimisation.
16	Severo, et al. [53]	Impact of the COVID-19 pandemic on environmental awareness, sustainable consumption and social responsibility: Evidence from generations in Brazil and Portugal	2021	An analysis of the impact of COVID-19 on environmental awareness in relation to various generations.
17	Brezet, et al. [54]	LCA for ecodesign: the Dutch experience	1999	Evaluation of various LCA industrial eco-design case studies to extract limitations and opportunities.
18	Schröder, et al. [55]	Making the circular economy work for human development	2020	A novel hybrid framework for human development focused circular economy.
19	Thomas, et al. [56]	Research Issues in Sustainable Consumption: Toward an Analytical Framework for Materials and the Environment	2003	Central research questions are addressed within the context of industrial ecology.
20	Tseng, et al. [57]	Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: a data driven analysis	2021	Bibliometric analysis of sustainable industrial and operations engineering in relation to Industry 4.0.
21	Raffaeli, et al. [58]	Sustainable strategies: a continuously improving methodology	2021	An 11-step continuous improvement methodology for environmental and economic performance.
22	Phuong and Guidat [59]	Sustainable value stream mapping and technologies of Industry 4.0 in manufacturing process reconfiguration: A case study in an apparel company	2018	Sustainable value stream mapping (SVSM) is applied in an apparel company to identify sustainability issues.
23	Xiao, et al. [60]	Using modified Barabási and Albert model to study the complex logistic network in eco-industrial systems	2012	An eco-industrial system is improved upon.

4.5. Steps 7 to 8: Data Extraction and Synthesis of Core Findings

The 23 publications from the SLR filtering process were all subjected to a full-text reading by one researcher. During this process, a thematic analysis was conducted using the atlas.ti software platform. Five sets of themes were formulated for industrial engineering knowledge and environmental sustainability knowledge. These codes were based on strategy, theory, methods, and practices that belong to each knowledge domain. The codes were formalised before the analysis and linked with the three business execution levels on strategic (strategies), operational (theories), and tactical (methods and practices) levels [61]. This was used to create a cascading application stream of each knowledge component, starting with strategic vision (strategies) leading to a theory which is eventually deployed as methods and practices. A knowledge component is a topic or recursive element that is featured in the analysis. Each theme received a dedicated code using atlas.ti. To establish the overlap, the co-occurrences of the codes are presented in Table 4. The GR codes refer to the code densities using atlas.ti. The numerical values at each code intersection represent a code overlap. According to the PRISMA checklists detailed by Page, et al. [38], the study characteristics are featured in Table 3. Furthermore, the results were reviewed and critiqued by two researchers in this study to reduce the risk of bias in the analysis and the reporting thereof.

Table 4. Industrial engineering and environmental sustainability code co-occurrence table.

		Environmental Sustainability (ES) Codes			
		ES Method Gr = 24	ES Practices Gr = 94	ES Strategy Gr = 61	ES Theory Gr = 55
Industrial Engineering (IE) codes	IE Methods Gr = 24	2	0	1	0
	IE Practices Gr = 44	2	7	1	1
	IE Strategies Gr = 19	0	1	1	0
	IE Theory Gr = 41	0	3	2	5

As can be elucidated from the table, there is a weak relationship between the various subsets of industrial engineering (IE) knowledge and environmental sustainability (ES) codes identified by a zero entry during the analysis. The strongest relationship is between the various practices and theories with a code density overlap in seven instances.

To better contextualise the interaction of the codes above, a network diagram has been forward-engineered and is presented in Figure 4. The code relations between each paper and respective code show an intricate web between IE theory methods and practices linked with ES theory, strategies, and practices across the various literature sources.

This diagram demonstrates the intricate link between the themes and publications as part of the data extraction and synthesis. It also outlines the term associations between each code being associated or a part of one another to demonstrate hierarchy and cascading forms of application across the three business execution levels. The knowledge components (theme codes in atlas.ti version 24.1.1) feature in dedicated tables, with each theme discussed in the subsections that follow.

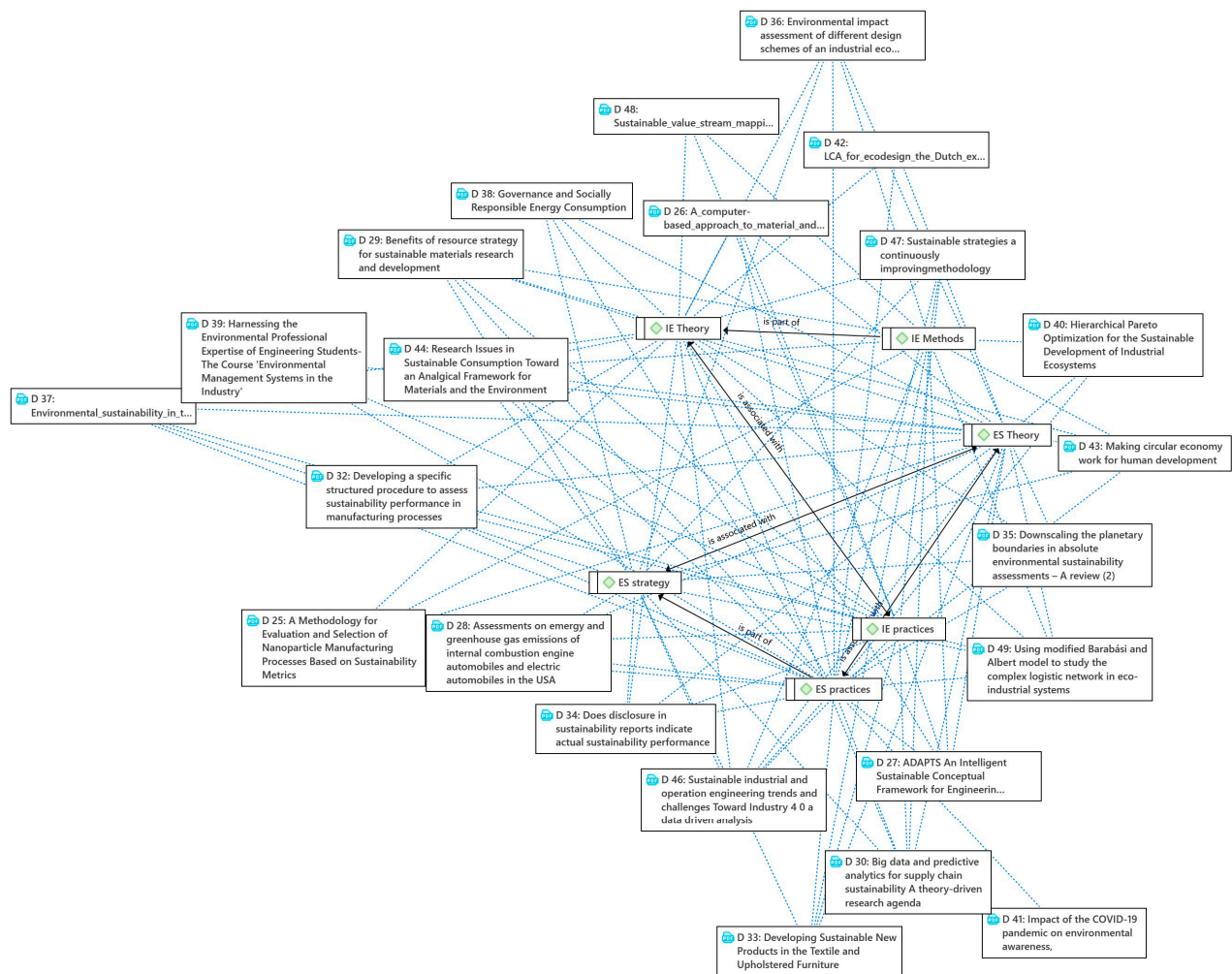


Figure 4. Network diagram for codes.

4.5.1. Strategy

Within IE knowledge, various strategies were revealed. These are further consolidated in Table 5. The numerical subscripts refer to the publications included in the thematic analysis, appearing in the order presented in Table 3. The succeeding tables will also contain these subscripts.

Table 5. Industrial engineering strategies.

IE Strategies	Paper References
Industry 4.0	[3,20]
Leapfrogging	[6]
Decision support systems and data analytics	[1,6]
Supply chain management (SCM)	[8]
Technology innovation	[6,8,18,19]
Risk mitigation	[5]
Product design	[8]
Resource consumption	[20]
Business strategy and profitability	[8,11,12]

Industrial engineers are believed to be able to pioneer the adoption of Industry 4.0 technologies. It can be argued that Industry 4.0 may support sustainable manufacturing by creating capabilities for product reuse, remanufacture, recycling, and reduction is a motivation for sustainable manufacturing [57]. Industry 4.0 technologies can create a smart manufacturing ecosystem paradigm since they create smart products and procedures that facilitate product reuse, remanufacturing, recycling, and reduction.

Technology leapfrogging is seen as the radical adoption of advanced technology where immediate prior technology has been absent [62]. For developing countries, this would allow companies to leapfrog foreign competitors [45]. Leapfrogging can be linked with a form of innovation and obtaining marketplace while being environmentally compliant. Hazen, et al. [45] believe that by leveraging big data and predictive analytics and applying this to resources and firm expertise, a marketplace advantage can be obtained. Furthermore, a decision support system becomes a crucial component when evaluating sustainability metrics, as explored by.

Unfortunately, environmentally focused efforts do not always yield financial gain for organisations [63]. It is therefore crucial that any simultaneous hunt for profit gains, technological innovation, and environmental performance is better understood. When promoting innovation, new product development, product differentiation, and increasing market appeal render a new solution that can disrupt a market.

Corporate sustainability has evolved as a business strategy initially perceived as abstract [51]. One such strategy can be used to improve supply chain operations. Dangelico, et al. [47] postulate that a collaborative supply chain aids in the development of green solutions. Risk mitigation strategies are also crucial to an organisation for the sustainable use of functionalized resources [44].

Industrial engineers pride themselves on efficacy. According to Galán-Martín, et al. [64] and as discussed by Tagliari, et al. [46], quantifying the sustainability level of a system or model is challenging considering various economic, environmental, and social aspects.

When reflecting on the ES domain, more sustainable principles are presented as strategic choices industries or organisations may employ. ES strategies are encapsulated in Table 6.

Various environmental sustainability strategies have been identified in the literature. While the IE strategies identified technology leapfrogging, Schröder, et al. [55] suggest lifestyle leapfrogging as an approach to avoiding fixed linear consumption patterns. This inherently configures circular systems and new business models that include sustainable consumption choices in developing countries. In relation to Industry 4.0, this helps to recover resources, reduce resource consumption, and increase resource allocation [57].

An emergent strategy was closely linked with supply chain management, more specifically, configuring closed-loop supply chains. Closed-loop supply chains could have negative employment outcomes for workers in low- and middle-income countries.

The most popular strategy obtained in this research was the circular economy (CE). The CE concerns itself with the conversion of goods at the end of their lifecycle into resources for others by creating closed loops that minimize waste and create industrial ecosystems [65]. Tseng, et al. [57] suggest that when applying this to a digital environment, increased utilization and resource efficiency are obtained through a redistributed application of used products. A digital environment is considered a method of applying emerging innovative technologies to recover usable material from used products and redistribute them in the production line [57]. CE practices and circular thinking can simultaneously promote human well-being and address environmental challenges [55]. This is a greater need in developing countries in the pursuit of job creation and improved health. The CE also aids in achieving several UN Sustainable Development Goals (SDGs).

Environmental considerations should be unbiased towards any point in a development cycle [51]. In contrast to popular opinion, Life cycle analysis (LCA) has proven to be contentious, inefficient, and expensive [56], and so efforts should be made to explore other

forms of evaluating environmental performance. In order to increase environmental reputation and develop green products, a product stewardship strategy can be employed [47].

Table 6. Environmental sustainability strategies.

ES Strategy	Paper Reference
Circular economy and sharing principles	[3,5,10,18,20]
Resource strategy, resource conservation (reduce, reuse, recycle)	[5,9,11]
Reducing carbon footprint, emissions, and energy (Reduce carbon)	[4,5,9,11]
Triple bottom line	[6]
Scientific knowledge creation	[6]
Environmental protection, management	[6,9,19]
The resource-based view	[6,8]
Low carbon impact, dematerialisation, decarbonisation and substitution (De-materialisation and carbonisation)	[8]
Green product and environmental innovation	[8]
Sustainable product development	[8]
Supplier evaluation	[9]
Reduce water consumption	[9]
Reduce energy consumption	[9,12]
Supply chain	[9,18,23]
Planetary Boundary	[10]
Eutrophication	[11]
Eco-effective symbiosis and an eco-industrial park	[11,19]
Clean production	[12]
LEED (Leadership in Energy and Environmental Design)	[12,18]
Sustainable resource management (SRM) and lifecycle thinking (LT)	[12]
Risk management	[13]
Energy labelling	[13]
Sustainable lifestyles	[18]
Global systems and engineered systems	[19]

The planetary boundary (PB) emerged as a strategy for achieving environmental sustainability as a conceptualized framework. PB provides a science-based analysis of the risk anthropogenic activities have in destabilizing the earth system at a planetary scale using nine boundaries for categorisation [66]. Being able to assess an activity relative to environmental boundaries perpetuates sustainability targets for said activity [49]. The nine boundaries possess safe operating spaces. According to Ryberg, et al. [49], an equal capita sharing of this space is advised across national, regional, and individual scales.

Large investments are needed in research and development [51]. Ryberg, et al. [49] suggest that R&D explores operational methods for sharing a safe operating space among humans and industrial units to maximise human welfare and capabilities.

What becomes rather apparent from these results is that any sustainability driven strategy must be symbiotic. Any strategic venture must have duality, trying to solve for a sustainability aspect alongside a profit, safety, cost saving, or productivity component.

The formulation of a sustainability driven strategy can vary. In one instance, Sen [67] believes that a symbiotic strategy can exist between sustainability development and differentiation. Another approach is to integrate a sustainability approach in its intended context, most considerably in a business context.

4.5.2. Theory

As the strategies now cascade into respective forms of theory, Table 7 provides the pertinent IE theory related to this research.

Table 7. Industrial engineering theory.

IE Theory	Paper Reference
Lean	[9,17,20–22]
Analytical models, algorithms, and machine learning	[1,3,6,7,11,18,20,23]
Multicriteria decision analysis	[1]
Facility planning	[2]
Value engineering and value creation	[3,5,6]
Simulations	[3,11,20]
Supply chain sustainability, reversed logistics, and closed-loop supply chains	[6,8,12,18,23]
Risk management	[13]
Game theory	[13]
Green engineering	[19]

Lean is an inherent industrial engineering philosophy that strives to reduce inefficiencies so as to improve organisational productivity [68]. By considering an inefficiency as high resource consumption or pollution, environmental sustainability improvements can be made by adopting Lean into an organisation. Lean manufacturing combined with Industry 4.0 can result in improved performance [57].

Various mathematical principles emerged in the analysis. The use of simulations, algorithms, machine learning, and decision analysis offer ways of modelling system behaviour and evaluating environmental performance metrics for optimal integration with production [41,42].

Configuring closed-loop supply chains with reverse logistic aspects can increase resource efficiency and create circular value chains. This ultimately leads to new value creation [47]. The various environmental sustainability theory is now presented in Table 8.

Industrial ecology is classified as a subset of ES theory despite being a transdisciplinary knowledge domain. Thomas, et al. [56] argue that industrial ecology strives to minimize costs and reduce environmental impacts. According to Munhofen, et al. [69], the components of industrial ecology are industrial metabolism, dematerialization, life cycle assessment, eco-design, and eco-industrial parks.

Tools for eco-design include the Lifecycle Expert Analysis of Design Strategies (LEADS) and an advanced methodology for environmental product development [54]. LEADS is a knowledge-based system for ranking DFE options using an environmental profile and assessment method [70].

Several social sciences theories in the form of agency, actor–network, social capital, and distributive justice theories. Actor–network theory systematically considers the infrastructure surrounding technological achievements with social relations as network effects. Agency Theory describes the relationship between entities that assigns tasks to one another [45]. This sophisticated network can be applied to supply chain management by explaining the interaction and flows of information, finance, and physical products [71,72].

As for distributive justice theories, utilitarianism, prioritarianism, sufficientarianism, egalitarianism, and libertarianism surfaced during the analysis. Building on the planetary boundaries framework, these justice theories can be used to define best practices using sharing principles that downscale according to seven dimensions [49]. Another social construct is that of coercive pressures and mimetic forces. According to Hazen, et al. [45], coercive pressures aid in the adoption of sustainable practices, while mimetic forces can result in organizations embodying sustainable traits from leading companies in their sector.

Resource dependence theory suggests that sharing principles are evident with organizations that lack resources and naturally develop relationships with other organizations [45,73].

Table 8. Environmental sustainability theory.

ES Theory	Paper Reference
Sustainable development and sustainability models	[1,7]
Environmental Management Systems	[1]
Building Information Modelling (BIM)	[3]
Life cycle analysis (LCA)	[3,8–10,19]
Cradle to cradle (C2C)	[3]
System boundary and planetary boundaries framework	[4,10]
Ecological engineering and modernization theory	[4,6]
Agency Theory (AT)	[6]
Environmental reform	[6]
Green manufacturing	[8]
Greenwashing	[9]
Institutional and distributive justice theory	[9,10]
Design for Environment (DFE) principles	[12]
Moore’s Law	[12]
Product and human ecology	[12,13]
Game theory	[13]
Cleaner and safer production	[14]
Industrial ecosystems and eco-industrial systems	[11,15,23]
LEADS (Lifecycle Expert Analysis of Design Strategies)	[17]
STRETCH	[17]
Circular humansphere	[18]
Industrial ecology	[19]

Risk analysis is complementary to the industrial engineering profession. It can be used to make strategic decisions. However, Seifi [24] argues that game theory is the most useful tool for strategic decisions considering risk management and analysis. Game theory is an economics and mathematical approach used for multi-actor decision making using game elements [74]. These strategic decisions can offer more effective decisions that concern environmental trade-offs.

One could also argue that systems will naturally reach a more sustainable state. Moore’s law can also be associated with sustainability. The exponential advancement of technologies also results in energy efficiency gains and performance indirectly impacts environmental performance [51].

4.5.3. Methods and Practices

The methods and practices theme has omitted tables since the results became more fragmented. Due to these low code densities, they are clustered into various discussions. Methods and practices are blended in this subsection with methods more theory-specific and practices represented with more of a practical backing.

Quantitative methods in the form of linear regression, algorithms, simulations, Bayesian and neural networks, multi-objective optimization, structural models, and decision support systems were prevalent as industrial engineering methods [41,42,50].

An Ishikawa (fishbone) diagram also emerged as a common industrial engineering tool used for primary and secondary cause identification and can be applied to any context, even for environmental concerns [58].

A green supply chain can be achieved by managing supply chain functions, vertical integration, outsourcing, and sourcing [45,60]. Careful supplier selection and development aid in reducing the carbon footprint of an organisation as well.

In order to obtain increased efficiencies, resource and energy efficiency during industrial upscaling must be systematically applied during a transformation [44,47]. Furthermore, determining bottlenecks or benefits aids in generating cost savings that can be used to invest in new (cleaner) technologies [46], renewable energy, or waste heat recovery technologies [44].

These are to be integrated within existing systems to promote product innovation and the re-engineering of products, processes, and technological systems [42,45,56]. These all warrant external and internal integrative, technological, and marketing-related capabilities [47]. Embodying these capabilities absorbs critical knowledge and resources using collaborative networks.

A business culture with shared goals, expectations, systems, values, and efforts helps differentiate customer value. It also strives to obtain the highest quality and minimum or reduced costs [40,42]. To effectively sustain this, training programs and creating incentives are key [45,47]. Furthermore, environmental ethics should be integrated into business culture [51].

Sustainable manufacturing and net zero emissions are attracting more research interest [57,58]. This can also seek out continued environmental improvement that abides by process and safety metrics that are continuously monitored [40]. Material to eco/sustainability is also reduced since the degree to which a material consumes energy and releases emissions is modified [40].

When considering the environmental sustainability aspects, one area of overlap with industrial engineering is the adoption of ISO standards [45], more specifically, the ISO 9000 and 14000 series [32,48,50,54]. Both are among the most widely known standards that are implemented across the globe. ISO 9000 focuses on quality concerns, while ISO 14000 addresses environmental management issues [75]. This can also be used as a model for corporate sustainability [32].

Life cycle analysis is one of the most prominent method of assessing the environmental impacts of products and services [40,47]. This procedure of evaluating and analysing environmental impacts uses an extensive set of input and output data on material and energy at different production stages [50]. However, Brezet, et al. [54] stresses that LCA lacks standardization and is not yet appropriate for computing environmental effects or performing external comparisons. It can, however, be effective in validating green design options amidst poor energy mixes. Adaptions include the ReCiPe method. The lifecycle thinking analysis methodology aids in the eco-design phase in organizations. Traditional environmental methods such as carbon footprinting, reducing pollution, and the 3Rs and smart waste management are also featured in the analysis [43,51,55,57].

Environmental policies and legislature reinforce governance and a commitment towards actionable forms of practice for environmental sustainability. The Organisation for Economic Co-operation and Development (OECD) Environment Directorate reports on policy initiatives that promote more sustainable consumption patterns [56]. More examples of policies or schemes include the IPCC, Eco-Management and Audit Scheme (EMAS), Kyoto Protocol, Montreal Protocol, GRI, and Rio Declaration [32]. Environmental policy and taxes require strict environmental auditing for compliancy. There are also public environmental policies that can be used in green operation or to facilitate a green product design [47].

Sustainability and eco-auditing are more actively being applied in industries [40]. Environmental accounting, or green accounting, is a tool to assist with environmental and operational costs that concern natural resources [76]. This specialised accounting system

can also make considerations for materials, CO₂ emissions, and other budgets, permitting prescribed volumes of respective inputs without penalty [49,56]. This can even stem so far as to enable carbon trading and the selling of surplus carbon quotas between organizations in the same industry [47].

A novel method to measure environmental performance is to evaluate emergy. Emergy is defined as the availability of energy (exergy) directly or indirectly related to the transformation of a product or service [43,77]. It can also be associated with the indirect and direct energy consumption. This is further researched by focusing on emergy transformity and analysis along with the emergy society database [43,52].

As a means of evaluating performance, various performance metrics and evaluation methods are situated in the literature. The RobecoSAM's corporate sustainability assessment analysis, material circularity indicator (MCI), sustainability metrics, work environment index, Sector Competition Index (SCI), and end-of-life recycling rate [41,44,48,55]. The Kinder–Lydenberg–Domini (KLD) index and Global Reporting Initiative (GRI) are also used for ESG reporting purposes [48]. Evaluation methods include the Life Cycle Impact, the AICHe total cost, and absolute environmental sustainability assessments (AESAs) [49,50].

Resource consumption forms the crux of any environmental improvement initiative. The exact acquisition of raw materials and technical know-how helps build a more reputable environmental profile [40,47]. Eco-design practices can also be used to reduce material consumption. This can also be used to increase environmental awareness, leadership, and literacy [51,53]. Eco-labels can be used to inform consumers of the environmental effects of their consumption and encourage producers to increase environmental standards using the information they provide [78]. It is therefore apparent that this would transform organizations, supply chains, and consumers' mindsets and increase eco-efficiency [32,55].

4.5.4. Circle Packing Knowledge Components

To further the findings yielded from the thematic analysis, a circle packing diagram is used in conjunction with the body of knowledge categorisation by the Institute of Industrial and Systems Engineering (IISE). The IISE Body of Knowledge identifies knowledge areas that apply to the field of industrial engineering, as illustrated in Figure 5.

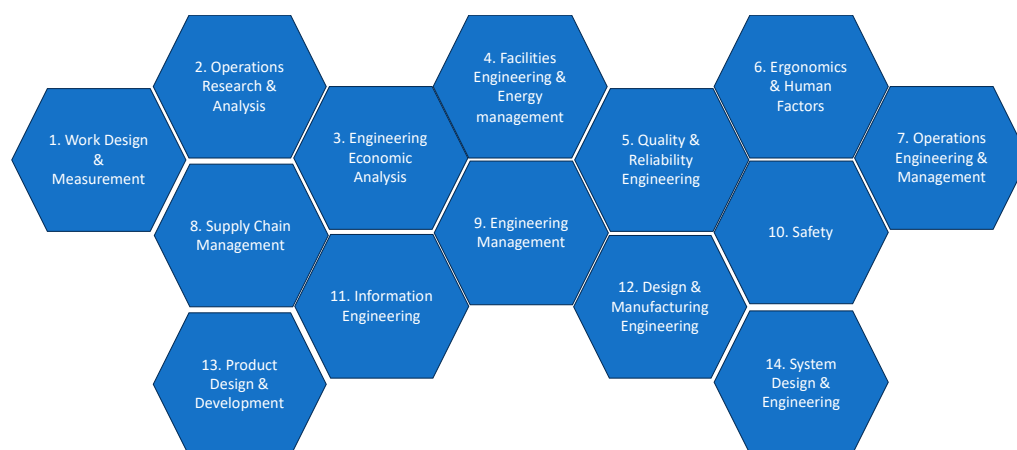


Figure 5. IISE Body of Knowledge, redrawn from (IISE) [23].

The shortcoming of this taxonomy model is that it does not speak to environmental sustainability. It does, however, present the core value of the industrial engineering profession, and so it becomes a cohesive way of structuring the findings. Using circle packing, a hierarchical structure is formed by linking each IE or ES strategy, theory, method, and practice that links with these body of knowledge areas. Figure 6 contains the legend (segmented for enhanced legibility), while Figure 7 presents the circle packing diagram that consolidates the findings from this research.

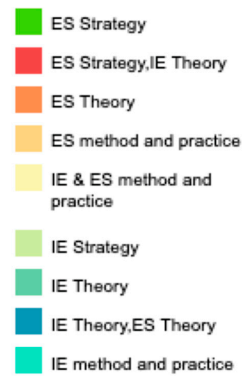


Figure 6. Legend for circle packing diagram.

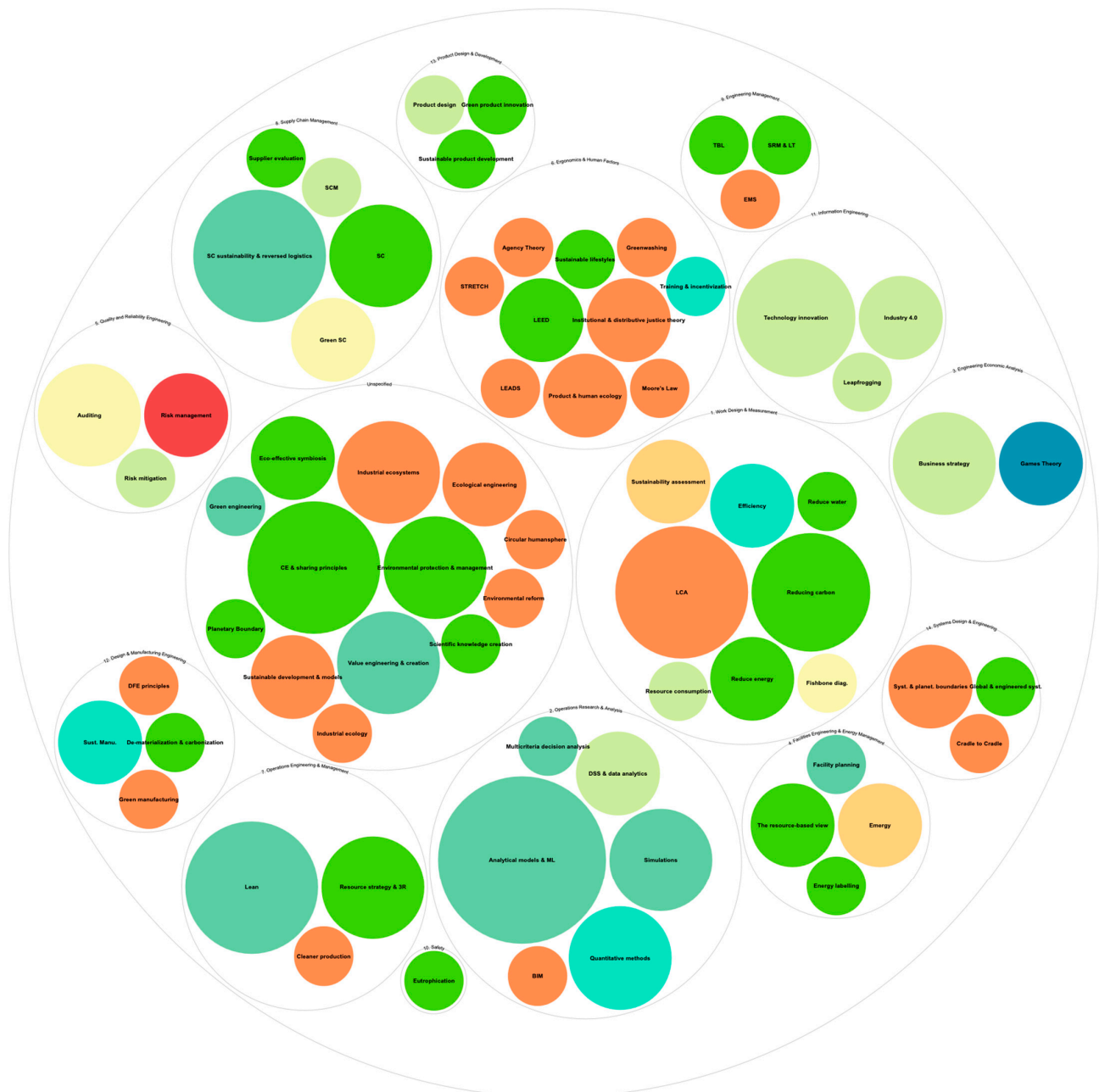


Figure 7. Circle packing diagram containing IE and ES knowledge components clustered according to the IISE body of knowledge areas.

The density (size) of each circle is a product of the code densities from the thematic analysis and is also associated with the authors identified in the literature review. The hierarchy is structured to align each knowledge component with the IISE Body of Knowledge areas. The current representation also hides knowledge components that overlapped text over each other which are later expanded. Unfortunately, some of the knowledge components did not conform to any of the body of knowledge areas, and so, an “unspecified” field has been created.

As illustrated in the diagram, the majority of these are associated with the ES theory, followed by an ES strategy. The diagram shows a healthy balance between the various knowledge component types within the IISE Body of Knowledge areas. Although holistic, it is possible to stratify the results and delve deeper into the knowledge areas and provide enhanced legibility. This stratification divides the 14 knowledge areas and unspecified fields into three parts containing five knowledge areas, respectively. The first five knowledge areas are presented in Figure 8.



Figure 8. Circle packing diagram containing first five knowledge areas.

The results showcase at least one of every knowledge type from the IE or ES. However, there are limited methods and practices for the first five knowledge areas. The engineering economic analysis knowledge area is the least represented with only IE knowledge components. This shortcoming reveals a lack of ES economic knowledge components reported in the literature. Figure 9 continues the presentation of the knowledge areas by showing knowledge areas 6 to 10.



Figure 9. Circle packing diagram containing knowledge areas six to ten.

With the IISE taxonomy classifications, ES strategies are dominant in knowledge areas six to ten, most noticeably with regard to ergonomics and human factors. A text overlap in engineering management hid the triple bottom line and sustainable resource management and lifecycle thinking. It is also evident that the IISE Safety Knowledge area is neglected in the literature. Figure 10 presents the remaining knowledge areas alongside an unspecified category which did not conform to the IISE classifications.



Figure 10. Circle packing diagram with the remaining knowledge areas and unspecified area.

Figure 10 tells us that the only IE strategic knowledge components linked with information engineering, the most imbalanced IISE knowledge area. For the design and manufacturing engineering knowledge area, a low carbon impact, dematerialization, decarbonization, and substitution overlapped with the sustainable manufacturing knowledge component. These results from the circle packing illustrations are further discussed in Section 5.

5. Discussion of Results

The realms of industrial engineering and environmental sustainability share innate links, some of which are dissociated and others that are synergetic. Only three knowledge components overlapped, namely green supply chain management, the circular economy, and technology management. There exist opportunities to use concepts such as Lean and Green and the transdisciplinary nature of industrial ecology to further environmental

improvements. Most of the results were siloed or fragmented, as was the case for most environmental sustainability knowledge components.

Lean is inherently associated with industrial engineering knowledge. The idea of green or environmentally conscious manufacturing with Lean can aid in more sustainable new products and increased sustainability performance [47,48]. A modified version of Lean is that of Lean and Green, which is a hybrid philosophy that strives to seek out simultaneous productivity improvements and environmental performance [34,79].

The idea of a green supply chain embodies traditional operations management and supply chain concepts from industrial engineering. Moreover, this has been identified and adopted under environmental sustainability aspects that incorporate amongst others reverse logistics and circular thinking. Supplier selection practices and material acquisition methods can be applied to have a more reliable, environmentally considerate and robust supply chain.

The circular economy is a sound means of reducing material consumption and waste. The industrial engineering discipline can further contribute towards more robust conceptualisation and implementation of circular thinking using the systems thinking instincts it has. More complex modelling approaches can be used to develop quantitative results on sustainability performance measures.

LCA is still a contentious matter that has polarised opinions. Some authors believe that with life cycle thinking, resource consumption and carbon footprints are systematically reduced, while others believe that it is not standardised enough. Nonetheless, there exist traits and characteristics of LCA that can be used to primarily facilitate environmental gains.

Technology development, integration, and readiness characteristics were uncovered in the research. Technology innovation and Industry 4.0 are becoming increasingly intertwined with environmental sustainability endeavours. Industry 5.0 is a newly coined term that remedies a shortfall of Industry 4.0, being distracted from social fairness (social sustainability) and sustainability and more focused on increasing production efficiency and flexibility [80]. It is therefore apparent that Industry 5.0 may be the more favourable term to use when discussing environmental considerations. The term Industry 5.0 was not associated with any of the literature obtained during the SLR, and so more practical methods to carry out environmental sustainability can be linked with strategies, theory, methods, and practices going forward.

The Quadruple Helix Model was originally developed by Carayannis and Campbell [81] towards conceptualising four components of an innovation system: academia, industry, government, and society. The results from this study have direct implications for the applications it can have in engineering education, industry implementation, and policy making. For governments, the formulation of policies and measuring conformance in local contexts can be inspired by some of the results obtained. ISO standards and reporting standards can be enforced in more industries. Furthermore, the adoption of new policies can be inspired using environmental sustainability aspects but carried out using change management theory from industrial engineering.

The circle diagram presents the various knowledge components as features within the distinct body of knowledge categories. It proposes that environmental sustainability is far reaching, with 13 knowledge components unspecific to the categories. The safety category is the least populated area, hinting that research in this field is explored in more detail and documented in the literature more evidently.

6. Conclusions, Limitations and Future Research

This study provides a state-of-the-art exploration of how the knowledge of the industrial engineering profession may appeal to environmental sustainability. This research establishes symbiotic relationships between aspects of IE knowledge that achieve environmental sustainability through strategies, theory, methods, and practices discussed. Although currently stratified, these results can be pieced together to form innovative solutions that harness industrial engineering knowledge primarily. It is argued that industrial

engineering can be seen as transdisciplinary or can at least promote or cultivate new forms of transdisciplinary knowledge areas that can appeal to broader contexts. The findings from this research can be enhanced by more explicit strategic, tactical, and operational approaches that can be informed by the strategies, theories, and methods and practices filtered in this study. Using implementation science, this can be transcended into more of a transdisciplinary problem-solving paradigm using industrial engineering. These results can inform policies concerning the triple bottom line and ESG reporting.

A paradigm shift is needed as a core steppingstone to blend concepts from these two subsets of knowledge between respective multidisciplinary, interdisciplinary, and transdisciplinary domains. The exact assortment of these concepts is yet to be established. Future research can develop frameworks or conceptual models that help with the adoption of various forms of knowledge or practically involve subject matter experts with industrial engineering or environmental sustainability experience. This can be used to create contextualised solutions to problems that can be solved via this hybrid combination.

According to Dangelico, et al. [47], organizations do not possess the necessary environmental knowledge and competencies to develop green products. Therefore, the eco-design process combined with industrial engineering process thinking can offer new methodologies or approaches for green product design. This can transcend DFE principles, cradle to cradle, life cycle analysis, and eco-design into more robust methods applied in industries.

A drawback from this study is that the findings are unspecific to a particular industry, and perhaps more importantly, not contextualised to any region or country. Researchers and practitioners can further this study by modifying these results for applicability in its area of application.

Technology management, industrial ecology, and green supply chain management were considered to overlap between industrial engineering and environmental sustainability knowledge in this study. Industrial ecology was the only form of transdisciplinary knowledge that featured in the results. Lean and Green could also be a hybrid philosophy that can be included. It is therefore of particular interest to consider the vast array of industrial engineering principles that can be modified as singular or collective forms of theory or strategies. This would then dictate the relevant methods and practices that can be used to practically implement solutions from these hybrid concepts or ways of thinking.

Furthermore, the articulation of the circle packing diagram representation argues that environmental sustainability can be intrinsic to the industrial engineering body of knowledge. While this shows a symbiotic relationship through the high degree of interconnected concepts, there is an evident gap in knowledge components accentuated by the unspecified field. Future research could explore a new class or categorisation that formalises the environmental sustainability paradigm with the industrial engineering body of knowledge.

This research provides a novel overview by finding the nexus between industrial engineering and environmental sustainability using results from the SLR, thematic analysis, and circle packing aligned with the IISE Body of Knowledge. It is the first research of its kind to explore the relationship between industrial engineering and environmental sustainability knowledge. The circle packing diagram can be analogised with spores which grow and spread similarly to how knowledge finds itself as seeds initially (infancy), diversifying and growing (spore development) and cross-pollinating to sustain itself (dissemination and preservation). These results can be used to create new transdisciplinary knowledge that can aid in addressing environmental challenges using the knowledge components obtained.

Author Contributions: M.R. contributed towards the conceptualisation, data curation, investigation, methodology, formal analysis, and writing—original and visualisation. R.S. aided in the supervision and writing—review and editing. R.C. assisted with the conceptualisation. All authors have read and agreed to the published version of the manuscript.

Funding: The authors received no financial support for the research, authorship, and publication of this article.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Das, T.K. *Industrial Environmental Management: Engineering, Science, and Policy*; John Wiley & Sons: Hoboken, NJ, USA, 2020.
2. Xiong, J.; Xu, D. Relationship between energy consumption, economic growth and environmental pollution in China. *Environ. Res.* **2021**, *194*, 110718. [CrossRef] [PubMed]
3. Stearns, P.N. *The Industrial Revolution in World History*; Taylor & Francis: Abingdon, UK, 2020.
4. Ramalingam, B.; Clarke, P.K. Meeting the urban challenge: Adapting humanitarian efforts to an urban world. In Proceedings of the Meeting the Urban Challenge: Adapting Humanitarian Efforts to an Urban World, Washington, DC, USA, 17–19 January 2012; p. 31.
5. Ameen, R.F.M.; Mourshed, M.J. Urban environmental challenges in developing countries—A stakeholder perspective. *Habitat Int.* **2017**, *64*, 1–10. [CrossRef]
6. Indriawati, R.M.; Gravitiani, E.; Soesilo, A.M.; Cahyadin, M. Long-term investigation of emissions and economic growth in developed and developing countries: A bibliometric analysis. *Int. J. Energy Econ. Policy* **2023**, *13*, 219–234. [CrossRef]
7. Mangaroo-Pillay, M.; Roopa, M.; Maisiri, W. Could digital Ubuntu be the South African version of industry 4.0? *S. Afr. J. Ind. Eng.* **2023**, *34*, 1–12. [CrossRef]
8. Darwish, H. *Expanding Industrial Thinking by Formalizing the Industrial Engineering Identity for the Knowledge Era*; North-West University: Potchefstroom, South Africa, 2018.
9. Goodland, R. The concept of environmental sustainability. *Annu. Rev. Ecol. Syst.* **1995**, *26*, 1–24. [CrossRef]
10. Kuhlman, T.; Farrington, J. What is Sustainability? *Sustainability* **2010**, *2*, 3436–3448. [CrossRef]
11. Morelli, J. Environmental sustainability: A definition for environmental professionals. *J. Environ. Sustain.* **2011**, *1*, 2.
12. Dittmer, L.D.; Reimer-Watts, K.; Dobai, J.; Riemer, M. Contributions, missed opportunities, and future directions: A critical reflection on global climate change and environmental sustainability in AJCP over five decades. *Am. J. Community Psychol.* **2023**, *72*, 288–301. [CrossRef]
13. Dörner, D.; Funke, J. Complex problem solving: What it is and what it is not. *Front. Psychol.* **2017**, *8*, 1153. [CrossRef]
14. Li, X.; Liu, D.; Sun, J.; Zhu, Z. Challenges of Industrial Engineering in Big Data Environment and Its new Directions on Extension Intelligence. *Procedia Comput. Sci.* **2022**, *214*, 1561–1567. [CrossRef]
15. IISE. What Is Industrial and Systems Engineering? (IISE Official Definition). Available online: <https://www.iise.org/Details.aspx?id=282> (accessed on 30 June 2024).
16. Darwish, H.; van Dyk, L. The industrial engineering identity: From historic skills to modern values, duties, and roles. *J. S. Afr. J. Ind. Eng.* **2016**, *27*, 50–63. [CrossRef]
17. Bowman, C.; Ambrosini, V. Value creation versus value capture: Towards a coherent definition of value in strategy. *BJM* **2000**, *11*, 1–15. [CrossRef]
18. Ozturk, O. Bibliometric review of resource dependence theory literature: An overview. *Manag. Rev. Q.* **2021**, *71*, 525–552. [CrossRef]
19. Sperotto, F. *In the Footsteps of Homo Industrialis: A Chronology of Industry and Industrial Engineering*; Production and Inventory Control, Systems and Industrial Engineering (PICSIE) Press: Buckingham, UK, 1994.
20. Bruner, R.F.; Miller, S.C. The great industrial revolution in Europe: 1760–1860. *SSRN Electron. J.* **2020**. [CrossRef]
21. Mangaroo-Pillay, M.; Roopa, M. Beyond the industrial engineering frontier: A few steps in history and a giant leap into the future. *S. Afr. J. Ind. Eng.* **2021**, *32*, 1–9. [CrossRef]
22. Salvendy, G. *Handbook of Industrial Engineering: Technology and Operations Management*; John Wiley & Sons: Hoboken, NJ, USA, 2001.
23. IISE. Institute of Industrial & Systems Engineering Body of Knowledge. Available online: <https://www.iise.org/details.aspx?id=43631> (accessed on 30 June 2024).
24. Seifi, S. Governance and Socially Responsible Energy Consumption. In *The Governance of Risk*; Emerald Group Publishing Limited: Bingley, UK, 2013; Volume 5, pp. 95–110.
25. Lang, D.J.; Wiek, A.; Bergmann, M.; Stauffacher, M.; Martens, P.; Moll, P.; Swilling, M.; Thomas, C.J. Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustain. Sci.* **2012**, *7*, 25–43. [CrossRef]
26. Tress, G.; Tress, B.; Fry, G. Clarifying integrative research concepts in landscape ecology. *Landsc. Ecol.* **2005**, *20*, 479–493. [CrossRef]
27. Lawrence, M.G.; Williams, S.; Nanz, P.; Renn, O. Characteristics, potentials, and challenges of transdisciplinary research. *One Earth* **2022**, *5*, 44–61. [CrossRef]
28. Stuart, J.A. Integration of industrial ecology concepts into industrial engineering curriculum. In Proceedings of the 2000 Annual Conference, St. Louis, MO, USA, 18–21 June 2000; pp. 5.379.1–5.379.8.
29. Fet, A.M.; Deshpande, P.C. Closing the loop: Industrial ecology, circular economy and material flow analysis. In *Business Transitions: A Path to Sustainability: The CapSEM Model*; Springer International Publishing: Cham, Switzerland, 2023; pp. 113–125.
30. Erkman, S. Industrial ecology: An historical view. *J. Clean. Prod.* **1997**, *5*, 1–10. [CrossRef]

31. Aarikka-Stenroos, L.; Ritala, P.; Thomas, L.D. Circular economy ecosystems: A typology, definitions, and implications. In *Research Handbook of Sustainability Agency*; Edward Elgar: Cheltenham, UK, 2021; pp. 260–276.
32. Ben-Zvi-Assaraf, O.; Ayal, N. Harnessing the environmental professional expertise of engineering students—The course: “Environmental Management Systems in the Industry”. *J. Sci. Educ. Technol.* **2010**, *19*, 532–545. [\[CrossRef\]](#)
33. Marco-Ferreira, A.; Stefanelli, N.O.; Seles, B.M.R.P.; Fidelis, R. Lean and Green: Practices, paradigms and future prospects. *Benchmarking Int. J.* **2019**, *27*, 2077–2107. [\[CrossRef\]](#)
34. Zokaei, K.; Lovins, H.; Wood, A.; Hines, P. *Creating a Lean and Green Business System: Techniques for Improving Profits and Sustainability*; Productivity Press: Cambridge, MA, USA, 2017.
35. Fink, A. *Conducting Research Literature Reviews: From the Internet to Paper*; SAGE Publications: Thousand Oaks, CA, USA, 2019.
36. Mangaroo-Pillay, M.; Coetzee, R. Lean frameworks: A systematic literature review (SLR) investigating methods and design elements. *Maig* **2022**, *15*, 202–214. [\[CrossRef\]](#)
37. Albliwi, S.; Antony, J.; Lim, S.A.; van der Wiele, T. Critical failure factors of Lean Six Sigma: A systematic literature review. *Int. J. Qual. Reliab. Manag.* **2014**, *31*, 1012–1030. [\[CrossRef\]](#)
38. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, 71. [\[CrossRef\]](#)
39. Rethlefsen, M.L.; Kirtley, S.; Waffenschmidt, S.; Ayala, A.P.; Moher, D.; Page, M.J.; Koffel, J.B. PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. *Syst. Rev.* **2021**, *10*, 39. [\[CrossRef\]](#)
40. Djassemi, M. A computer-based approach to material and process selection using sustainability and ecological criteria. In Proceedings of the PICMET’09-2009 Portland International Conference on Management of Engineering & Technology, Portland, OR, USA, 2–6 August 2009; pp. 2316–2321.
41. Naidu, S.; Sawhney, R.; Li, X. A methodology for evaluation and selection of nanoparticle manufacturing processes based on sustainability metrics. *Environ. Sci. Technol.* **2008**, *42*, 6697–6702. [\[CrossRef\]](#)
42. Luque, A.; Heras, A.D.L.; Ávila-Gutiérrez, M.J.; Zamora-Polo, F. ADAPTS: An Intelligent Sustainable Conceptual Framework for Engineering Projects. *Sensors* **2020**, *20*, 1553. [\[CrossRef\]](#)
43. Jing, R.; Yuan, C.; Rezaei, H.; Qian, J.; Zhang, Z. Assessments on emergy and greenhouse gas emissions of internal combustion engine automobiles and electric automobiles in the USA. *J. Environ. Sci.* **2020**, *90*, 297–309. [\[CrossRef\]](#)
44. Helbig, C.; Kolotzek, C.; Thorenz, A.; Reller, A.; Tuma, A.; Schafnitzel, M.; Krohns, S. Benefits of resource strategy for sustainable materials research and development. *Sustain. Mater. Technol.* **2017**, *12*, 1–8. [\[CrossRef\]](#)
45. Hazen, B.T.; Skipper, J.B.; Ezell, J.D.; Boone, C.A. Big data and predictive analytics for supply chain sustainability: A theory-driven research agenda. *Comput. Ind. Eng.* **2016**, *101*, 592–598. [\[CrossRef\]](#)
46. Tagliari, L.D.; Pandolfo, A.; Zeilmann, R.P. Developing a specific structured procedure to assess sustainability performance in manufacturing processes. *J. Clean. Prod.* **2020**, *269*, 122404. [\[CrossRef\]](#)
47. Dangelico, R.M.; Pontrandolfo, P.; Pujari, D. Developing sustainable new products in the textile and upholstered furniture industries: Role of external integrative capabilities. *J. Prod. Innov. Manag.* **2013**, *30*, 642–658. [\[CrossRef\]](#)
48. Papoutsis, A.; Sodhi, M.S. Does disclosure in sustainability reports indicate actual sustainability performance? *J. Clean. Prod.* **2020**, *260*, 121049. [\[CrossRef\]](#)
49. Ryberg, M.W.; Andersen, M.M.; Owsianiak, M.; Hauschild, M.Z. Downscaling the planetary boundaries in absolute environmental sustainability assessments—A review. *J. Clean. Prod.* **2020**, *276*, 123287. [\[CrossRef\]](#)
50. Singh, A.; Lou, H.H.; Yaws, C.L.; Hopper, J.R.; Pike, R.W. Environmental impact assessment of different design schemes of an industrial ecosystem. *Resour. Conserv. Recycl.* **2006**, *51*, 294–313. [\[CrossRef\]](#)
51. Harland, J.; Reichelt, T.; Yao, M. Environmental sustainability in the semiconductor industry. In Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment, San Francisco, CA, USA, 19–22 May 2008; pp. 1–6.
52. Singh, A.; Lou, H.H. Hierarchical pareto optimization for the sustainable development of industrial ecosystems. *Ind. Eng. Chem. Res.* **2006**, *45*, 3265–3279. [\[CrossRef\]](#)
53. Severo, E.A.; De Guimarães, J.C.F.; Dellarmelin, M.L. Impact of the COVID-19 pandemic on environmental awareness, sustainable consumption and social responsibility: Evidence from generations in Brazil and Portugal. *J. Clean. Prod.* **2021**, *286*, 124947. [\[CrossRef\]](#)
54. Brezet, H.; Stevels, A.; Rombouts, J. LCA for ecodesign: The Dutch experience. In Proceedings of the First International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, 1–3 February 1999; pp. 36–40.
55. Schröder, P.; Lemille, A.; Desmond, P. Making the circular economy work for human development. *Resour. Conserv. Recycl.* **2020**, *156*, 104686. [\[CrossRef\]](#)
56. Thomas, V.M.; Graedel, T.E. Research issues in sustainable consumption: Toward an analytical framework for materials and the environment. *Environ. Sci. Technol.* **2003**, *37*, 5383–5388. [\[CrossRef\]](#)
57. Tseng, M.-L.; Tran, T.P.T.; Ha, H.M.; Bui, T.-D.; Lim, M.K. Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: A data driven analysis. *J. Ind. Prod. Eng.* **2021**, *38*, 581–598. [\[CrossRef\]](#)
58. Raffaelli, R.; Rossi, M.; Cappelletti, F. Sustainable strategies: A continuously improving methodology. *Int. J. Interact. Des. Manuf. (IJIDeM)* **2021**, *15*, 151–154. [\[CrossRef\]](#)

59. Phuong, N.A.; Guidat, T. Sustainable value stream mapping and technologies of Industry 4.0 in manufacturing process reconfiguration: A case study in an apparel company. In Proceedings of the 2018 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI), Singapore, 31 July–2 August 2018; pp. 85–90.
60. Xiao, Z.; Zhou, G.; Wang, B. Using modified Barabási and Albert model to study the complex logistic network in eco-industrial systems. *Int. J. Prod. Econ.* **2012**, *140*, 295–304. [\[CrossRef\]](#)
61. Schmidt, G.; Wilhelm, W.E. Strategic, tactical and operational decisions in multi-national logistics networks: A review and discussion of modelling issues. *Int. J. Prod. Res.* **2000**, *38*, 1501–1523. [\[CrossRef\]](#)
62. Fong, M.W. Technology leapfrogging for developing countries. In *Encyclopedia of Information Science and Technology, Second Edition*; IGI Global: Hershey, PA, USA, 2009; pp. 3707–3713.
63. Revell, A. The ecological modernisation of SMEs in the UK's construction industry. *Geoforum* **2007**, *38*, 114–126. [\[CrossRef\]](#)
64. Galán-Martín, Á.; Guillén-Gosálbez, G.; Stamford, L.; Azapagic, A. Enhanced data envelopment analysis for sustainability assessment: A novel methodology and application to electricity technologies. *Comput. Chem. Eng.* **2016**, *90*, 188–200. [\[CrossRef\]](#)
65. Stahel, W.R. The circular economy. *Nature* **2016**, *531*, 435–438.
66. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; De Vries, W.; De Wit, C.A. Planetary boundaries: Guiding human development on a changing planet. *Sciences* **2015**, *347*, 1259855.
67. Sen, S.K. Symbiotic linkage of sustainability, development and differentiation. *Compet. Rev. Int. Bus. J.* **2014**, *24*, 95–106.
68. Womack, J.P.; Jones, D.T.; Roos, D. *The Machine That Changed the World*; Simon & Schuster: London, UK, 2008.
69. Munhofen, J.; Myers, A.; Ng, K.; Nierenberg, L.; Nosal, C.; Nowak, M. Industrial Ecology. 1995. Available online: <http://www2.dnr.cornell.edu/saw44/NTRES331/Products/Spring%202004/Powerpoints/IndustrialEcologyPresentation.pdf> (accessed on 19 August 2024).
70. Rombouts, J.P. LEADS-II. A knowledge-based system for ranking dfe-options. In Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment ISEE-1998 (Cat. No. 98CH36145), Danvers, MA, USA, 13 May 1998; pp. 287–291.
71. MacIntosh, R.; MacLean, D. Conditioned emergence: Researching change and changing research. *Int. J. Oper. Prod. Manag.* **2001**, *21*, 1343–1357. [\[CrossRef\]](#)
72. Kinder, T. Go with the flow—A conceptual framework for supply relations in the era of the extended enterprise. *Res. Policy* **2003**, *32*, 503–523. [\[CrossRef\]](#)
73. Ulrich, D.; Barney, J.B. Perspectives in organizations: Resource dependence, efficiency, and population. *Acad. Manag. Rev.* **1984**, *9*, 471–481. [\[CrossRef\]](#)
74. Bekius, F.; Gomes, S.L. A framework to design game theory-based interventions for strategic analysis of real-world problems with stakeholders. *Eur. J. Oper. Res.* **2023**, *309*, 925–938. [\[CrossRef\]](#)
75. Muralikrishna, I.V.; Manickam, V. Chapter Ten—ISO 9000, 14000 Series, and OHSAS 18001. In *Environmental Management*; Muralikrishna, I.V., Manickam, V., Eds.; Butterworth-Heinemann: Oxford, UK, 2017; pp. 177–208. [\[CrossRef\]](#)
76. Muralikrishna, I.V.; Manickam, V. Chapter Seven—Environmental Accounting. In *Environmental Management*; Muralikrishna, I.V., Manickam, V., Eds.; Butterworth-Heinemann: Oxford, UK, 2017; pp. 113–134. [\[CrossRef\]](#)
77. Amaral, L.P.; Martins, N.; Gouveia, J.B. A review of emergy theory, its application and latest developments. *Renew. Sustain. Energy Rev.* **2016**, *54*, 882–888. [\[CrossRef\]](#)
78. Gallastegui, I.G. The use of eco-labels: A review of the literature. *Eur. Environ.* **2002**, *12*, 316–331. [\[CrossRef\]](#)
79. Farias, L.M.S.; Santos, L.C.; Gohr, C.F.; Oliveira, L.C.d.; Amorim, M.H.d.S. Criteria and practices for lean and green performance assessment: Systematic review and conceptual framework. *J. Clean. Prod.* **2019**, *218*, 746–762. [\[CrossRef\]](#)
80. Xu, X.; Lu, Y.; Vogel-Heuser, B.; Wang, L. Industry 4.0 and Industry 5.0—Inception, conception and perception. *J. Manuf. Syst.* **2021**, *61*, 530–535. [\[CrossRef\]](#)
81. Carayannis, E.G.; Campbell, D.F.J. 'Mode 3' and 'Quadruple Helix': Toward a 21st century fractal innovation ecosystem. *Int. J. Technol. Manag.* **2009**, *46*, 201–234. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Chapter 5

5 Identifying Harmony between Industrial Engineering and Environmental Sustainability in South Africa

This chapter serves as a research paper **published** in the Journal of **Sustainable Futures** (Q1).

Abstract: Industrial engineering (IE) has become globally recognised for transforming operational improvements across organisations. Yet, its relationship with environmental sustainability (ES) is an issue with both growing fixation and sporadic literature on the topic. Despite this, there remains limited consensus on its relationship. South Africa is among the many developing countries challenged with achieving ES, and IE knowledge may be the resolution.

This research strives to uncover the relationship between IE and ES for a Sustainable Competitive Advantage (SCA), an aspect of literature faintly explored within transdisciplinary contexts. A qualitative research methodology was adopted, using an interpretive approach incorporating interviews. The results from 24 interviews were analysed using thematic analysis, revealing various knowledge components segmented into strategies, theories, methods and practices. The results outline knowledge components that complement both IE and ES knowledge domains. These suggest ways to establish synergy which produces operational and environmental gains for organisations universally by incorporating notions such as Circular Economy, Systems Thinking, Sustainable Transitions, Lean, Project Management, Simulation modelling, Industry 5.0, ESG reporting, and Value Stream Mapping. This research demonstrates synergy points between Industrial Engineering and Environmental Sustainability that can create transdisciplinary knowledge for a sustainable competitive advantage. Although derived from the population interviewed, the results boast a promising relationship between these two knowledge domains and welcome further research to amalgamate these paradigms within transdisciplinary knowledge contexts for societal challenges.

Keywords: Industrial Engineering; Environmental Sustainability; South Africa; Interview; Sustainable Competitive Advantage; Transdisciplinary knowledge

Doi: <https://doi.org/10.1016/j.sftr.2026.101695>

Introduction: Chapter 5 reproduces the second published research output of the thesis and marks a deliberate methodological pivot from the literature-only design (Chapter 4), toward primary, practitioner-sourced data. Where Chapter 4 established that IE and ES knowledge are weakly connected in the published literature, Chapter 5 asks whether that same association holds when industrial engineers and environmental practitioners working in South Africa are asked directly. The chapter opens by reaffirming the industrial engineering global reputation for operational improvement, while noting the mounting evidence that these operational gains have compounded environmental pressure rather than relieved it. It situates South Africa specifically within the wider challenge facing developing countries, namely that achieving environmental sustainability is complicated by infrastructure constraints, poorer energy mixes, overpopulation pressures and resource depletion, and that organisations in this context are increasingly turning to a sustainable competitive advantage (SCA) as a strategic response that aligns economic, social and environmental objectives.

The chapter explicitly builds on Chapter 4 (cited internally as Roopa et al.), acknowledging that the earlier SLR-based results were generic, literature-bound, and not contextualised to South Africa or connected to the SCA concept. This is presented as the precise gap Chapter 5 exists to close. A theoretical background section, structured using a systematic text condensation technique (Malterud, 2012). It revisits the IE-ES relationship, the evolution of sustainability models (Mickey Mouse, triple bottom line, embedded/bullseye), and the historical, methodological and practical reasons the two fields have remained fragmented, before introducing sustainable competitive advantage as the unifying construct that gives the practitioner interviews their strategic purpose.

Relevant research component: The research problem is stated plainly: there are no clear knowledge components between Industrial Engineering and Environmental Sustainability for a sustainable competitive advantage in South Africa, a gap said to hinder both organisational competitiveness and the broader adoption of sustainability narratives as a regional concern. The research aim is to identify hybrid knowledge components in industry and academia for a sustainable competitive advantage in South Africa. Two objectives operationalise this aim: to explore the relationship between IE and ES from literature and subject-matter experts for an SCA in South Africa, and to use that relationship to extract knowledge components that contribute to an SCA within transdisciplinary knowledge contexts. These objectives are matched to two explicit research questions, RQ1 ("What SCA synergy points exist between IE and ES?") and RQ2 ("How do the knowledge components compare with the existing body of knowledge?"), with RQ1 addressed through the interview programme and RQ2 addressed through thematic analysis and comparison against Chapter 4's literature-derived results. The chapter explicitly frames itself as transdisciplinary in nature, since it combines academic and non-academic (industry) knowledge sources to solve a shared, complex societal problem.

Methodology: Chapter 5 adopts a qualitative, interpretive research design built around in-depth, semi-structured online interviews with industrial engineers and environmental managers or practitioners across South Africa, deliberately drawing from both academia and industry to preserve the dual dichotomy required of genuinely transdisciplinary knowledge production. Participants were recruited using purposive, snowball sampling, initiated through an independent intermediary (to reduce respondent resistance) and researcher networks including LinkedIn scraping. The inclusion criteria limited to participants holding at least four years of IE or ES experience. Guided by literature supported sample-size recommendations for open-ended interview research, an initial

target of fifteen participants was set as a floor. For data saturation, the stop criteria from Francis *et al.* (2010) was employed, which includes the three additional papers given. The criteria were met if there was any repetition amongst already-mentioned peers or when code frequencies for a knowledge component exceeded two. Saturation was reached after 21 interviews and confirmed with three further confirmatory interviews, yielding a final sample of 24 participants with an average of 17.8 years of combined IE/ES experience.

Interviews, conducted over Microsoft Teams and lasting between 30 and 45 minutes, followed a structured protocol adapted from (Creswell & Creswell, 2017). This was built around three core questions mapped explicitly onto the strategic, tactical and operational business execution levels used in Chapter 4. All interviews were recorded, transcribed, and coded by a single primary observer in atlas.ti, with the coding scheme and project file shared with a second researcher for validation, and reliability and validity were addressed through verbatim low-inference reporting, member-appropriate briefing, and comparison against the existing literature. An initial set of eleven codes was refined down to five, of which the first three, strategies, theories, and methods and practices, constitute the substantive knowledge-component taxonomy reported in the findings. Ethical clearance was obtained from the North-West University Research Ethics Committee, with pseudonymisation applied throughout to protect participant identity.

Core findings: The 24 interviews yielded a substantial dataset: 374 coded examples collapsing into 143 distinct knowledge components across the strategy, theory, and methods-and-practices categories (code counts of 82, 156 and 136 respectively before refinement). At the strategic level, systems thinking, circular economy, and sustainability transitions emerged as the dominant strategic knowledge components, with participants repeatedly describing waste reduction and resource efficiency as the "golden thread" connecting IE and ES. At the theoretical level, Lean (and its hybrid Lean and Green variant) was identified by eleven participants as directly translatable into environmental gains, alongside a wide span of management theories (project, supply chain, quality, financial, risk and energy management), optimisation theory, and biomimicry. At the operational level, ESG reporting, data analysis, recycling, the R-paradigms (3R/6R/12R), and value stream mapping were the most frequently cited methods and practices, though the discussion also surfaces important nuance, for example those recycling and reverse logistics are not unconditionally beneficial and can, in some cases, consume more energy than they save.

The discussion section explicitly reconciles these interview findings with the existing literature, including direct comparison against Chapter 4's SLR results, and against related South African research (Tsoku *et al.*, Machado *et al.*). It concludes that a moderate but genuine synergy exists between IE and ES, sufficient to support an SCA, but that this synergy must be actively cultivated through top-down strategic alignment rather than assumed to emerge organically. Biomimicry and Industry 5.0 are highlighted as particularly promising, underexplored theoretical bridges. Ultimately, the chapter reports that 143 knowledge components, more than four times the handful of overlaps found in Chapter 4's literature review. This can be meaningfully harmonised between IE and ES for an SCA in the South African context, directly answering both RQ1 and RQ2.

Reflections: This chapter demonstrates that the fragmentation Chapter 4 identified in the literature is considerably less severe in practice than it appears on paper since practitioners on the ground already intuitively bridge IE and ES far more readily than the formal literature or professional taxonomies currently document. This is an important and

somewhat counter-intuitive finding, since it implies that the intent of this research is not to invent a connection between IE and ES from nothing, but to formalise and structure a connection that already exists tacitly in professional practice. The rigour applied to sampling and saturation (Francis et al.'s stop-criteria, the 17.8-year average experience of participants) lends considerable credibility to this claim, and the explicit cross-referencing against Chapter 4's results throughout the discussion demonstrates methodological accountability within the thesis.

At the same time, the chapter is candid about its limitations where the findings are confined to the population interviewed, generalised across all sectors despite the transdisciplinary framing, and silent on how the 143 knowledge components should be sequenced, weighted, or prioritised relative to one another, a gap the chapter explicitly. These were all classed as falling outside the scope of the study. This is a deliberately open thread, since resolving it becomes the central task of Chapter 7. The chapter's own future-research section anticipates this almost exactly, calling for mixed-methods and quantitative approaches capable of weighting and validating these qualitative insights, effectively pre-announcing the Pareto-Weighted Thematic Analysis that Chapter 7 goes on to develop.

Inter-relationships across other chapters: Chapter 5 sits in direct methodological continuity with Chapter 4: it reuses the same three-tier (strategic/tactical/operational) classification scheme, the same atlas.ti coding infrastructure, and explicitly benchmarks its interview-derived knowledge components against Chapter 4's SLR-derived ones, treating the earlier chapter as both a point of comparison and a source of legitimacy. Its own output, the 143-component, 374-example interview dataset, becomes, alongside the 23 publications from the SLR corpus (Chapter 4), one of the two raw data sources fed directly into Chapter 7's Pareto-Weighted Thematic Analysis and the resulting TD artefact. Ultimately, without Chapter 5's interviews, the TD artefact (presented in Chapter 7) would have no grounded data associated with practitioners, speaking to the relevance cycle of the DSR cycle. As for the lighthouse model (chapter 6), though developed independently and largely in parallel using literature only, it draws on some of the same South African IE literature base and the same transdisciplinary framing, and is itself later listed as one of the antecedent artefacts feeding into the abstraction phase of its methodology created. Finally, several of the specific knowledge components first surfaced through Chapter 5's interviews, including systems thinking, circular economy, VRIO-adjacent resource-based views, and Dynamic Capabilities. These reappear directly as evaluative frameworks in Chapter 9's use case analysis, demonstrating that Chapter 5's practitioner-sourced vocabulary persists as a narrative leading to its final validation chapters.



Identifying harmony between industrial engineering and environmental sustainability in South Africa

Meelan Roopa ^{*}, Raj Siriram

School of Industrial Engineering, North-West University, South Africa

ARTICLE INFO

Keywords:

Industrial engineering
Environmental sustainability
South Africa
Interview
Sustainable competitive advantage
Transdisciplinary knowledge

ABSTRACT

Industrial engineering (IE) has become globally recognised for transforming operational improvements across organisations. Yet, its relationship with environmental sustainability (ES) is an issue with growing fixation and sporadic literature on the topic. Despite this, there remains limited consensus on its relationship. South Africa is among the many developing countries challenged with achieving ES, and IE knowledge may be the resolution. This research strives to uncover the relationship between IE and ES for a Sustainable Competitive Advantage (SCA), an aspect of literature faintly explored within transdisciplinary contexts. A qualitative research methodology was adopted using an interpretive approach incorporating interviews. The results from 24 interviews were analysed using thematic analysis, revealing various knowledge components segmented into strategies, theories, methods and practices. The results outline knowledge components that complement both IE and ES knowledge domains. These suggest ways to establish synergy which produces operational and environmental gains for organisations universally by incorporating notions such as Circular Economy, Systems Thinking, Sustainable Transitions, Lean, Project Management, Simulation modelling, Industry 5.0, ESG reporting, and Value Stream Mapping. This research demonstrates synergy points between Industrial Engineering and Environmental Sustainability that can create transdisciplinary knowledge for a sustainable competitive advantage. Although derived from the population interviewed, the results boast a promising relationship between these two knowledge domains and welcome further research to amalgamate these paradigms within transdisciplinary knowledge contexts for societal challenges.

1. Introduction

1.1. Context

Industrial Engineering (IE) is a multidisciplinary profession yielding operational improvements across sectors globally [1,2]. It promises balanced integration between people, processes, technology, and material by designing mental and physical artefacts that extract value from our highly interconnected world [3,4]. Engineers have historically contributed towards environmental problems, but are now more crucial in achieving and more responsible for Environmental Sustainability (ES) [5]. IE is non-exempt. While the industrial engineer has bestowed many operational improvements across all sectors, they have indirectly created higher consumption rates [6,7]. This has been evidenced by the growing global material flow increasing from 22 billion tonnes in 1970 to 70 billion tonnes in 2010 because of growing wealth, consumption and increased trade [8]. The IE profession has inculcated several

operational principles that contribute negatively towards the environment. It is therefore befitting that they should help create solutions to environmental challenges [4,7].

In their defence, IE is recognised for fostering sustainability by improving efficiency through waste reduction [9]. Two popular IE taxonomy models exist, namely the International Institute for Industrial and Systems Engineering 14 bodies of Knowledge [1] (2021), and the IE knowledge domains by Salvendy [2]. The shortcoming of these well-established models is that they have no formal association with ES. This deficiency alludes to a disconnect between the IE and ES paradigms.

For developing countries, achieving ES is more complex amidst infrastructure development, poorer energy mixes, overpopulation, pollution and resource depletion [10,11]. The relationship between economic growth and environmental protection is further complicated by a heavy dependence on natural resources for economic development [12,13]. Organisations always want to remain competitive, now investing in obtaining a sustainable competitive advantage (SCA) as an

^{*} Corresponding author.

E-mail addresses: meelanroopa@sun.ac.za (M. Roopa), raj@alpha-concepts.com (R. Siriram).

<https://doi.org/10.1016/j.sfr.2026.101695>

Received 29 November 2024; Received in revised form 30 December 2025; Accepted 22 January 2026

Available online 29 January 2026

2666-1888/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

approach to embrace sustainable practices in the value offering that aligns economic, social and environmental objectives [14,15]. These organisations integrate sustainability into their business models [16].

Transdisciplinary research transcends beyond the loosely connected realms of scientific and academic boundaries by creating integrated knowledge through cooperation towards a single goal that has unifying aims and methodologies between researchers, practitioners and other stakeholders [17–19]. The traditional dichotomy of transdisciplinary knowledge considers theoretical vs practical modes [20]. According to Max-Neef [21], it offers a systematic and holistic view of the world cascading across several levels of reality and within organisations. In this way, more complex and systemic issues can be resolved. IE prides itself on its holistic view and systems thinking which makes it cognisant of the interrelationships between systems and big-picture thinking [22]. This positions the profession to lead transdisciplinary problem-solving projects. Alessandro et al. [23] believe transdisciplinary problem-solving will aid in solving the complexity of ES issues.

On a global scale, Kanchan et al. [24] argue that green practices within business contexts can promote a sustainable competitive advantage. The focus for a SCA for environmental reporting already differs between developed and developing countries. Kvasničková Stanislavská et al. [25] demonstrate that most developed countries prioritise supply chain emissions and sustainable production, while developing countries consider education and human rights imperative. In the emergent and developing country of India, a blend of these results complements their mixed economy it has. It was found that a critical factor for higher SCAs in their supply chains was a resource-based view (RBV) to ensure a competitive advantage [26]. South African research has tried to address environmental challenges and promote ES. Research on socio-technical transitions has explored an integrated framework to manage technology during sustainability transitions [27], Lean and Green performance [28] and modelling green economy transitions [29]. Roopa et al. [30] conducted a systematic literature review (SLR) to explore the link between IE and ES. The results were classed according to the IISE bodies of knowledge using knowledge components across the three decision-making levels (strategies, theories, methods and practices on strategic, tactical and operational levels). However, these results were too generic, contained knowledge components unspecific to the taxonomy model, purely literature-based, neglecting South Africa and not considering an SCA. This creates polarity between academia and industry, hampering transdisciplinarity prospects.

Despite the SCA advances for developing countries such as South Africa, IE taxonomy models neglect sustainability narratives. Furthermore, SCA is becoming a strategic mindset adopted within organisations, which is more challenging for developing countries. Developing countries also have a comparative advantage in developing competing strategies [31]. The research gap explored in this study is positioned at the epicentre of IE, ES, Transdisciplinary knowledge, and SCA. Although South African sustainability research exists, it lacks real-world context on the knowledge components needed for an SCA integrating IE and ES within transdisciplinary contexts.

1.2. Research problem

There are no clear knowledge components between Industrial Engineering and Environmental Sustainability for a sustainable competitive advantage in South Africa. This hinders competitiveness and the adoption of sustainability narratives as a regional concern.

1.3. Research aim

The research aim is to identify hybrid knowledge components in industry and academia for a sustainable competitive advantage in South Africa.

1.4. Research objectives and questions

The objectives to achieve the prescribed aim of this research are to:

1. Explore the relationship between IE and ES from literature and subject matter experts for a SCA in South Africa
2. Use the relationship to extract knowledge components that contribute to a SCA in South Africa within transdisciplinary knowledge contexts.

To support the research intent, the following research questions are formulated:

- RQ1: What SCA synergy points exist between IE and ES?
- RQ2: How do the knowledge components compare with the existing body of knowledge?

Objective 1 relates to research question 1 by employing interviews. Similarly, objective 2 resonates with research question 2, where thematic analysis is used to extract the knowledge components. This research is argued to be transdisciplinary since it combines research from IE and ES to solve a complex societal issue by retrieving information from multiple stakeholders that involved co-design, co-production and co-implementation. The paper is structured with a theoretical background in Section 2, the research design in Section 3, and associated findings in Section 4. A discussion follows in Section 5 before providing the conclusions, limitations and future research ideas in Section 6.

2. Theoretical background

The structure of the paper is a product of systematic text structure and condensation techniques applied. Systematic text structure and condensation are primarily focused on the cross-case analysis of various data types [32]. Kando [33] has long since believed that this is a systematic way of analysing, comparing and integrating information from multiple sources. The sources of textual information in this research stem from literature and interview data. Malterud [32] places a strong emphasis on the systematic text condensation technique being most favourable with interview and literature information. It is for this reason that the findings from the interviews (Section 3) are pre-emptively worded as a theoretical background for the discussions (Section 4).

2.1. Industrial engineering and environmental sustainability relationship

The IE profession prides itself on innovative problem-solving, integrated solutions, and often optimised systems and processes [4]. IE has embodied systems engineering as a core component of the profession [34].

Sustainability recognises society, economy and the environment. While this was initially siloed (“Mickey Mouse model”), over time this has morphed into an overlapping Venn diagram illustration (Triple Bottom Line) as elaborated by Mebratu [35]. Recently, this has been modified into an embedded bullseye diagram with the economy within society, embedded in the environment [7]. Environmental sustainability is built on the principle of protecting the sources of raw materials used for human needs that prevents harm to society by not having harvest rates exceed regeneration rates [36].

The realms of IE and ES are intertwined. As IE continues to innovate and create efficiency gains, this compromises the environment, which environmental practitioners must remedy. Similarly, any environmental solution warrants the need for further innovation.

However, these fields remain disconnected for historical, methodological and practical reasons. According to Haapala et al. [37], the rise of ES focuses on environmental policy and public discourse in comparison to the efficiency and productivity attention owed to process and systems origins of IE. Although Industrial Ecology is a transdisciplinary

knowledge field addressing industrial and environmental metabolisms, it is questioned due to its misconceptions and impractical applications [38]. Methodologically speaking, the approaches can differ in intent with productivity prioritised in engineering, unlike the systematic and conservative narrative in ES [37]. The work of Tseng et al. [39] divulges that although Industry 4.0 is an engineering accomplishment, the full potential of ES has not fully realised. A similar sentiment from Jabbour et al. (2018) found advanced technologies can elevate Circular Economy (CE) strategies but is unfortunately not the case. Despite the engineering advances being made, the environment is still left behind.

Barriers to implementing sustainability and engineering solutions are constantly researched. Luthra et al. [40] explored green supply chain barriers where governmental and institutional processes emerged among other multidisciplinary structures and constraints. Engineering workflows, supply chain relationships and governmental structures remain as impeding forces for engineering solutions and sustainability transitions [40–42].

The methodological and practical reasons speak to execution and implementation concerns when trying to integrate IE and ES. Perhaps of more concern is the fundamental strategic misalignment that exists due to historical reasons. This positions strategic (historical), tactical or theoretical (methodological) and operational (practical) reasons at disarray. This is also observed by Roopa et al. [30] who classify these as fragmented knowledge components. The underlying aim of this speaks to a sustainable competitive advantage, which organisations need to pursue.

2.2. Sustainable competitive advantage

The goal of any organisation is to generate profit [43]. Competitiveness has driven up material consumption, leading to the reinforcement of more sustainable business practices [44]. A positive relationship already exists between sustainability innovation and firm competitiveness [45]. In this research, firms will be phrased as organisations. For an SCA, it needs to have a durable advantage with a clear gap in capability vs. competitors [46]. The efforts made by organisations must embrace sustainability in their fundamental strategic approach to outdo competitors [47–49].

SCA becomes more focused when exploring firm competitiveness and sustainable firm performance. This can be improved through sustainable supply chains and green practices [50]. Another sustainability innovation is to explore socio-technical transitions. Socio-technical transitions emerged in the early 2000s as research from the field of

innovation studies that tries to best understand the future and nexus of complex sustainability issues [51]. In South Africa, efforts have been made to build a competitive advantage using South African Ubuntu [52], explore open innovation alignment within an automotive supply chain [53], and societal marketing concepts at local retailers [14]. However, none have explored SCA using IE and ES knowledge.

3. Research design

3.1. Research approach and strategy

This research takes the form of a qualitative study by asking questions that concern the real world [54]. According to Derkachenko and Kononiuk [55], qualitative research is argued as an appropriate means to resolve sustainability challenges since it provides insights into human-environment interaction. This study seeks to understand the link between IE and ES in practice using questions stratified on three levels cast across the three execution levels in an organisation [56]. These levels are strategic, tactical and operational, which can be aligned with the levels of organisational decisions and processes for decision-making in general [57,58]. This research argues that the application of knowledge cascades with strategies, theories and methods and practices as visualised in Fig. 1.

Similar to Roopa et al. [30], strategies are defined as any vision that gives organisations a sense of direction. Furthermore, this calls on theory (specialised subject matter or concepts) which is implemented using methods and practices that represent best practices, procedures, tools and techniques. Each knowledge component can be positioned at a strategic (strategies), tactical (theories) or operational (methods and practices) level. This cascading application stream runs top-down across the business execution levels.

3.2. Research method

3.2.1. Research setting

Qualitative, in-depth online interviews were conducted with industrial engineers and environmental managers or practitioners in South Africa. Since this research strives to create transdisciplinary knowledge, members from academia and industry were consulted. This ensured two dichotomies of transdisciplinary knowledge that are balanced and to include non-academic stakeholders during the knowledge production process [20].

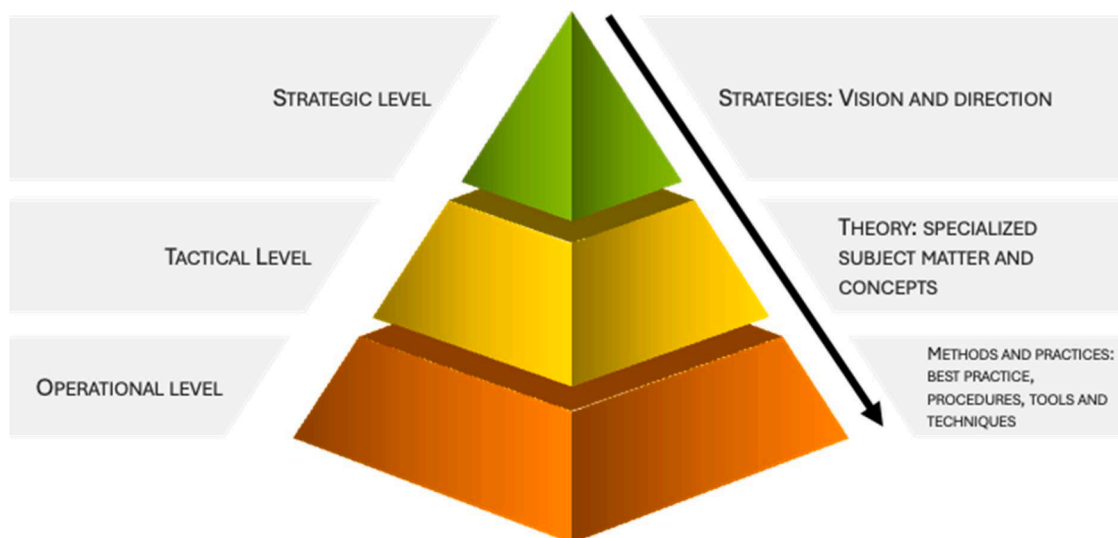


Fig. 1. Business execution level and knowledge component categorisation inspired by Roopa et al [30].

3.2.2. *Entre   and establishing researcher’s role*

To reduce respondent resistance [59], an independent person first made email contact by providing the informed consent request and interview information. The initial set of participants was first identified using networks belonging to the researchers and from LinkedIn web scraping.

3.2.3. *Sampling*

This study employed a purposive, snowballing sampling strategy [60]. This non-probability sampling technique proves beneficial for hidden populations that may exist [61]. This ensured in-depth information across the network, as justified by Noy [62]. Despite its bias in pre-empting the population, it can yield a good representation of a unique population [63]. In addition, the bias can be reduced using a stringent interview protocol to ensure consistency, reliability and validity [64].

The inclusion criteria sought participants with at least four years of IE or ES experience in their organisation. According to Weller et al. [65], a sample size of 15 people can capture 95 % of the most salient ideas in open-ended interviews. Guest et al. [66] also suggest that 12 interviews are sufficient to reach data saturation. As a failsafe, the larger sample size suggestion is taken in this research. This led to an initial sample set of 15 participants, culminating in 24 participants being interviewed after saturation was reached.

3.2.4. *Data collection method*

Interviews were consistently conducted using the structured guidance of an interview protocol [64]. Table 1 represents the interview protocol employed to reduce participant bias and ensure the credibility of findings.

Each question is centred around identifying IE and ES knowledge components specific to the business execution levels. Probing questions were open-ended for consistency amongst the sample while maintaining engagement to prevent disjointed dialogues and cohesion [67].

3.2.5. *Data recording*

Thorsteinson [68] found that longer interview lengths do not compromise the reliability of the data, influencing interview duration between 30 and 45 min using recorded Microsoft Teams meetings. The recordings were used for quality control and to refine the automatically generated transcripts. The recordings and transcripts are the data source for this research. No null data featured in the analysis. Should this have occurred, the relative theme would not have been coded for.

3.2.6. *Strategies to ensure data reliability and validity*

In qualitative research, Brink [69] clarifies the difference between reliability and validity. Reliability focuses on the consistency, stability and repeatability of the interview encounter alongside interviewer

collection methods [70]. Validity considers the accuracy and truthfulness of scientific findings [71]. To ensure reliability, constant data comparisons were performed by immediately transcribing and coding the transcript. Additional data validation included clear mention of the purpose of the research to participants, making transcripts available and comparing the findings with the literature [69]. Participants received the same briefing and were allowed to ask for clarity. Internal reliability was sustained by having low inference descriptors that result in verbatim reporting [69]. Data saturation implied data validation according to saturation principles provided by Francis et al. [72], namely, that researchers must be specific on an initial analysis sample and set stop criteria. Per this, Table 2 has been crafted to represent the saturation identifiers. For theory-based interviews, Francis et al. [72] propose a minimum of 10 participants and an additional 3 interviews without new ideas as the stopping criteria for data saturation.

Data saturation was reached after interviewing and analysing the data from participant 20. The mention of already interviewed participants occurred during the 21st interview. Three additional interviews were thus conducted per the stop criteria. The code frequencies were consolidated to more than two for each knowledge component, indicating that saturation occurred. This sample size corroborates the prescriptive numbers for interview research between 20 and 30 participants [64]. Theoretical saturation occurred since no new theoretical insights emerged from the core theoretical categories in the analysis [73].

3.2.7. *Data analysis*

According to Alshenqeeti [74], coding can be used to analyse interview data. Thematic analysis (TA) was employed as a mechanism for identifying, analysing and interpreting patterns of meaning (themes) by coding the interview data [75]. This approach flexibly reduces the data and grants researchers the ability to explore various topics [76,77].

To ensure that the findings were credible, a single observer reviewed and coded the transcripts with atlas.ti for consistency. The analysis and project file were shared with the other researcher for further validation.

Table 2
Saturation identifiers employed in this research adapted from Francis et al. [72].

Saturation principle	Application
Initial analysis sample	15 interviews
Stop criteria	A sample size of 3 additional interviews will be conducted in an instance where both of the following events occurred: • Participants recommending already interviewed participants to be included in the study on two occasions • Code frequencies greater than two or more knowledge components under a strategy, theory and method or practice

Table 1
Research protocol inspired by Creswell and Creswell [64].

Purpose: Interview protocol to investigate the relationship between Industrial Engineering knowledge and environmental sustainability
Introduction: This research identifies the relationship between Industrial Engineering and environmental sustainability knowledge components. This study is a first in a series of studies contextualising Industrial Engineering knowledge in terms of its applicability to environmental sustainability. It considers how Industrial Engineering can act as a catalyst in creating new forms of transdisciplinary knowledge areas. It also considers how Industrial Engineering knowledge can contribute to environmental challenges.
You have been identified as a candidate because you are an Industrial Engineering or Environmental manager or practitioner in South Africa. Some of these questions explore the relationship between Industrial Engineering (IE) and Environmental sustainability (ES). There are three questions. For each question, you can also request for more context, in which case, the researcher will provide more details from an earlier phase of this research.
Main research question: What is the relationship between Industrial Engineering knowledge and environmental sustainability knowledge?
Question 1: What strategies can you identify that share a relationship between (are applicable to both) Industrial Engineering and environmental sustainability that ensure sustainable competitive advantages?
Probing questions: What Environmental sustainability strategies can be linked with Industrial Engineering? How do some of strategies facilitate environmental sustainability?
Question 2: What theories can you identify that share a relationship between (are applicable to both) Industrial Engineering and environmental sustainability that ensure sustainable competitive advantages?
Probing question: What Environmental sustainability theories can be linked with Industrial Engineering?
Question 3: What methods and practices can you identify that share a relationship between (are applicable to both) Industrial Engineering and environmental sustainability that ensure sustainable competitive advantages?
Probing question: How do some of these facilitate environmental sustainability?

The analysis was not rushed, and data from participants were used for theme generation, discussions and conclusions [77]. Furthermore, the codes were reviewed in two iterations. An initial set of 11 codes was truncated to five. The first three codes (strategies, theories, methods and practices) embody the three categories of knowledge components. The remaining two codes entailed general discussion points and links between IE and ES. To ensure transferability, the results were made generalizable by adhering to IE and ES nomenclature. The analysis process is disclosed for research credibility. The codes were then used to align with the three levels of knowledge components that cascade across an organisation.

3.2.8. Ethical considerations

Ethical considerations by De Vos et al. [78] were employed. Participants were contacted by an independent researcher. Participation was entirely voluntary, and they could withdraw from the study at any stage. During data collection, the information was not distorted and pseudo-anonymisation was applied to protect the identity of participants. The findings from the study and analysis have not been altered or misrepresented. No environmental data were explicitly retrieved in this research. Should any such information have emerged during data collection, a factor reduction or normalisation would have been performed before coding.

Using this established research design, the findings are presented in Section 4.

4. Research findings

4.1. Sample characteristics

To profile the participants, the primary industry (predominant years) was identified. Table 3 provides this information alongside the number of years and the knowledge component contribution that match the atlas.ti code frequencies. Pseudonymity has been ensured with each participant linked with a participant ID.

The codes reveal the cumulated codes and not their densities. The results were further consolidated and refined. The codes ranged from 82, 156 and 136 codes for strategies, theories, methods and practices to 30, 53 and 70 codes respectively. These codes have densities ranged from 1 to 11. The sample contained an average of 17.8 years of experience, indicative of vast IE and ES experience with diverse industry representation.

4.2. Knowledge component association and composition

To demonstrate the structure of the codes used in the analysis, Fig. 2 outlines the network architecture between concepts articulated in this research.

Fig. 2 showcases the interaction between the codes. It demonstrates the cascading knowledge components and problem-solving nature owed to IE and ES challenges implicitly linked with respective advantages. To unpack the results and their associations with the three knowledge components, Fig. 3 identifies the interconnectedness between each IE and ES component with the three clustered knowledge components.

The integration between each IE and ES feeds into each of the three knowledge components. The respective advantages, challenges and motivations align with each knowledge component across all business execution levels.

The next subsections elaborate on the strategies, theories and methods and practices obtained from the thematic analysis. Only core knowledge components are discussed.

4.3. Strategies

At a strategic level for any organisation, a SCA remains pivotal for the integration of IE and ES domains [30]. Table 4 contains the strategic

Table 3

Sample characteristics of primary industry and contributions to each knowledge component.

ID	Primary Industry	Years	Strategies	Theories	Methods and practices
P1	Energy sector	20	2	6	1
P2	Academia, Technology management	40	2	2	2
P3	Energy utilities, environmental consulting	15	3	12	16
P4	Mining	20	6	7	6
P5	Academia, Innovation	10	3	6	1
P6	Automotive	14	1	4	4
P7	Mining	17	4	2	7
P8	Plastic manufacturing	4	1	2	4
P9	Academia, Sustainability	8	6	12	2
P10	Academia, Industrial Engineering	16	4	13	8
P11	Academia, Industrial Ecology, Systems thinking	29	4	13	4
P12	Logistics	15	7	3	2
P13	Academia, Industrial Engineering	24	3	4	1
P14	Business consulting	35	5	14	10
P15	Academia, Manufacturing systems	24	1	2	9
P16	Environmental consulting	16	2	4	8
P17	Academia, Innovation	27	6	10	7
P18	Automotive	21	1	4	6
P19	Supply chain management	5	3	7	7
P20	Logistics	23	4	10	7
P21	Supply chain management	8	2	4	6
P22	Academia, Environmental sustainability	15	5	8	6
P23	Entrepreneurship	10	2	4	2
P24	Food manufacturing	13	5	3	10
	Total		82	156	136

area of focus along with the participant ID for each individual interviewed. For example, [9] indicates participant 9 mentioned the Sustainable Development Goals in Table 4.

Although 29 different strategies were obtained during the interview, only the core strategies are clustered and discussed further.

4.3.1. Systems thinking

Systems thinking proves to be a novel approach to solving problems of complexity that are non-reductionist, enabling a holistic view of the problem situation. It looks at interactions and connections between the different parts of a systems[79,80]. This therefore makes systems thinking an ideal approach to study the connectivity between IE, ES and CE (discussed in Section 4.2.2).

Aligned with this view on systems thinking, participant 4 (P4) voiced that systems thinking solutions are non-exact and entail a diverse set of integrated components. P11 stated that most, if not all Industrial engineers are systems thinkers, yet to formally incorporate ES. Systems thinking and efficiency-driven strategies were also dominant knowledge components among participants. According to Siriram [81], systems thinking can improve competitive capabilities within organisations. Further research from Siriram and Plessis [80] uncovered that systems thinking develops firm competitiveness while paving the way to sustainable solutions and firm performance. Their work also suggests that VUCA environments be explored, an environment where this transdisciplinary research orientates itself. The industrial engineer can identify and create productivity and efficiency gains from resources and operations by IE employing systems and holistic thinking to addresses

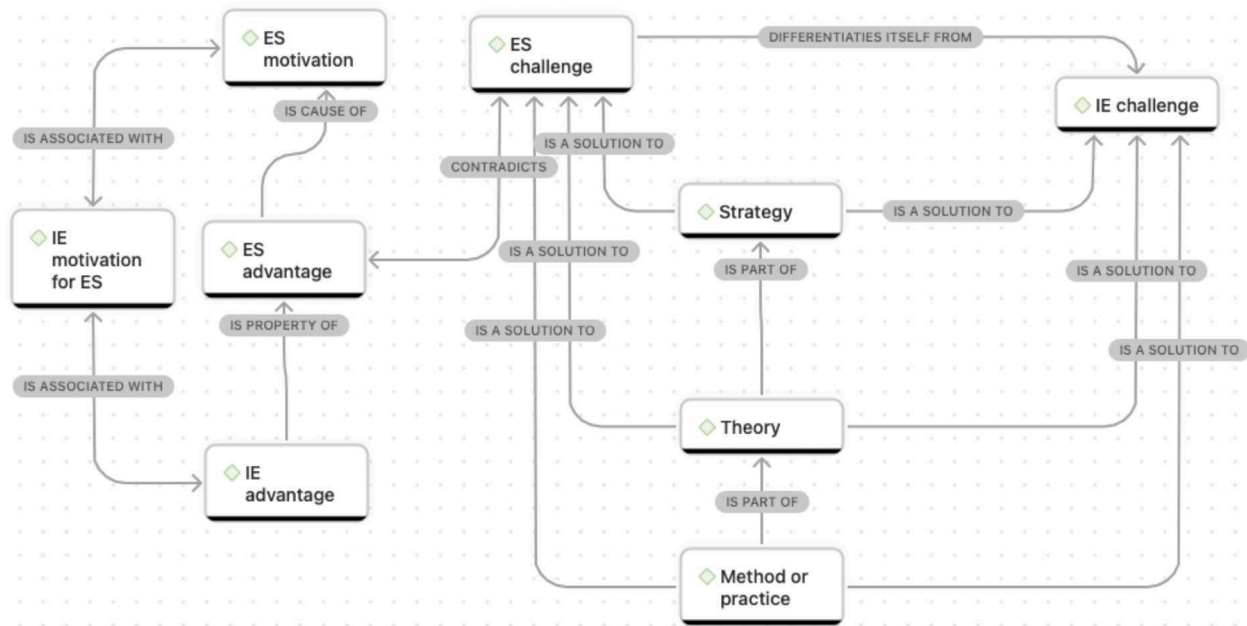


Fig. 2. Codes and knowledge component network architecture using atlas.ti.

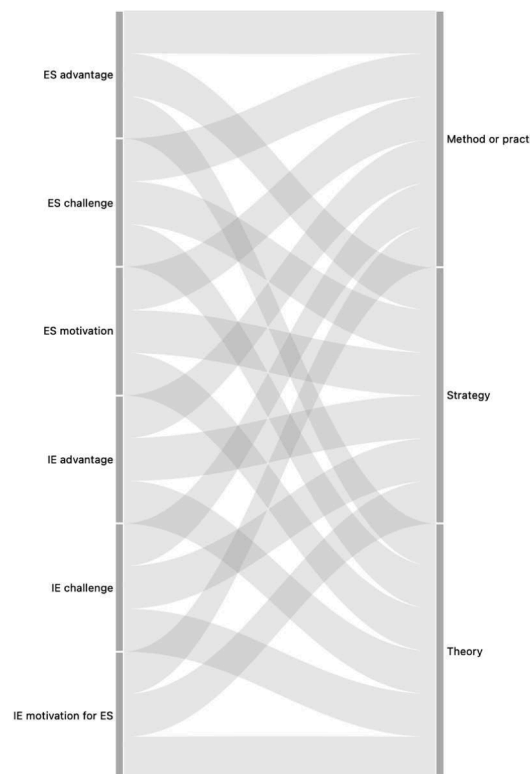


Fig. 3. Knowledge components vs. IE and ES paradigm code Sankey diagram.

the entire value chain (P4). Industrial Engineers view the entire process or system as the “big picture” (P18). Participant 24 argued that the golden thread between IE and ES is the reduction of waste and utilisation of resources. This “efficiency” trait allows them to translate this approach towards environmental efficiency and performance, as also evidenced by the work of Garcia-Garcia et al. [82] who reduced food manufacturing waste and resource usage when combining Business Process Re-engineering and Industry 4.0 within IE contexts.

4.3.2. Circular economy

Although Circular Economy (CE) is a systematic way of thinking, it differs to systems thinking since it shifts from linear reductionist to circular holistic thinking, focusing on sustainability and economic decoupling [79]. CE needs to be embedded into any sustainability narrative (P3). Circular thinking cannot be overlooked. In any undertaking, one must consider all parts of the system and how one can facilitate the circular economy as a whole (P11). An interesting take on CE is that it allows a service economy to become more sustainable (P22), and link with servitization to extend the product life cycle and warranties, creating higher resource utilisation rates over time. This complements the work of Stahel [83], who articulates that a service economy increases resource productivity. This service sector instils more skill-intensive output with specialised skills forming [84]. This could help service economies such as South Africa with large populations by creating more jobs, incurring more income with durable assets, and ensuring more functional value from a product within a circular system. One can monetise the waste stream with circularity (P22) or close supplier loops similar to how participant 23 achieved this in a startup company. Some challenges do exist, namely the financial constraints and capital investment required to create closed-loop systems [85]. Another daunting task is to ensure technical constraints and technology implementation do not negatively impact efficiency, customer value, products or systems when adopting circular economy principles.

4.3.3. Sustainability transitions

Socio-technical transitions are part of the IE suite that can aid in business innovation (P9,P10). Sustainability transitions are needed on a strategic level (P9, P11). A multi-level perspective (MLP) facilitates the sustainability narrative (P5,P9,P12). It is also pertinent that we understand socio-technical systems and how technology is used in a sustainable way (P22). Participant 9 contests the current sustainability narrative by declaring that organisations should seek out ways to improve sustainability around them as opposed to within their functions. In other words, apply sustainability extrinsically (How) and not only intrinsically (Why). This could entail an extrinsic carbon trading reward system vs. an intrinsic training program on environmental awareness. Often with competitive advantages, organisations apply sustainability extrinsically instead of intrinsic value [86].

Table 4
Strategies that promote environmental sustainability.

Strategy	Context	Participant(s)
Sustainable Development Goals	United Nations Goals for sustainability	[9,12,13,17,18,21,22,23,24]
Circular economy	R paradigm closed loop application for valorisation	[3,4,10,11,14,20,21,24]
Systems thinking	Systems perspective on phenomena, processes and activities	[4,11,18,19,23]
Efficiency (resources and operations)	Use of resources sustainably	[6,14,15,22,24]
Culture integration	Multicultural integration	[1,5,11,22]
Socio-technical transitions	Shifts in technology interaction with social systems and structures	[9,10,11,22]
Technology & Innovation	Innovating using current or emergent technologies	[4,13,20]
Continuous improvement	Iterative and ongoing improvement strategies within organisations	[4,15,17]
Minimising waste stream	Reducing wasteful activities	[7,12,24]
Business models for sustainability	Sustainability knowledge components incorporated into business models	[9,11,13]
Carbon neutrality	Carbon footprint equivalent to its offset	[3,16]
People, Planet and Profits	Collective alignment across each business KPI	[1,4,14]
Cross disciplinary	Sustainability narratives beyond disciplines for high ordered problem solving	[12,13]
Data driven decision making	Decision making with quantitative techniques or inference	[17,24]
Monetization	Increasing economic activity within latent business attributes	[20,22]
Shared value	Collective value system configured	[5,10]
Corporate social responsibility	Ethical and responsible mindset towards economic, social and environmental sustainability	[10,12]
Decarbonization roadmap	Implementation framework towards less GHG emissions	[3]
Material substitution	Greener supplier or product selection	[4]
EFQM model	Global management framework for sustainable excellence	[4]
Resource-based perspective	A resource view that creates a SCA using internal resources and capabilities	[5]
High quality	Reliable products/systems that extend longevity to prevent overproduction	[10]
Reduce emissions	Lowering direct and indirect emissions	[12]
Radical redesign	Form of innovation specific to systems, products or processes	[17]
Maturity models	Mental artefacts on varied understanding and impact of sustainability	[17]
Reduce carbon footprint	Measuring and minimising carbon footprint	[19]
Life cycle view	Mapping and monitoring sustainability across all stages	[19]

These strategies all embody the instinctive productivity gains the IE profession has on society and the environment. For more explicit implementation, these strategies require the use of theories that are discussed in the next subsection.

4.4. Theories

Theories encompass a specific knowledge domain that requires understanding and shares multidisciplinary associations. Table 5 outlines the various forms of theory that emerged from the interviews.

Certain theories appear counterintuitive, such as machine learning, renewable energy development and cradle-to-grave. Machine learning encompasses extensive theoretical foundations [87], while renewable energy development is rooted in sustainable development theory from Sathaye et al. [88]. Similarly, cradle-to-grave is argued as a design theory according to Voorthuis and Gijbels [89].

4.4.1. Lean

Eleven participants believed that the principles of Lean can directly translate to environmental improvements. Lean is more than just a theory (P6). In general, IE focuses on the reduction of waste, which can be translated to water and energy saving efforts (P24). Environmental sustainability must also consider levels of maturity that would exist in the organisation (P17). The Lean and Green paradigm provides a framework that shows varying relationships that exist between the antecedent paradigms [90].

4.4.2. Management theory

Project, supply chain, quality, financial, product life cycle, operations, change, risk and energy management were retrieved from the coding as forms of management theory. These attest to the diverse theory domains that Industrial Engineers contribute to. Project management metrics are no longer just time, money and quality, but the environmental impact of the various activities (P11). Quality management and the implementation of Six Sigma can also be associated with environmental metrics (P9). Operations management is a major component of IE that ensures resources are not being wasted and naturally lends itself towards ES (P10). Financial management speaks to various feasibility studies that can sketch financial perspectives using ROI calculations for economic and environmental sustainability (P20). According to Neubert and Dyck [91], adaptations of management theory better suit sustainable practices for various stakeholders, as further explored in Section 4.4.

4.4.3. Optimisation

IE prides itself on its ability to harness optimisation theory. One can optimise resources and environmental performance using the lowest cost and environmental strain (P8). Alleviating bottlenecks improves operational efficiencies which indirectly reduces carbon intensity and creates emission, electricity and water savings (P3). Employing economies of scale and longer production runs also creates lower energy intensities with less consumption per unit (P6). These aspects can be modelled to understand cause and effect, and estimate potential financial or environmental gains from certain improvements [92].

4.4.4. Complex adaptive systems

Environmental challenges as part of complex adaptive systems. This is evidenced by product or technology interaction factoring the influence it has on a systems levels and sustainability dimensions (P4,P7,P9, P11,P14). Collaboration from a systems perspective is lacking significantly (P11), yet it provides multiple benefits for all parties if correctly executed and internalised. This deficiency has spurred the formulation of collaborative systems theory [93].

4.4.5. Supply chain management

Supply chain management and logistics management were identified as a core IE knowledge domain. However, we should define this as sustainable supply chain management instead (P24). This can be achieved by embracing circularity, applying reverse logistics and conducting a complete life cycle analysis across open and closed supply chains (P3,P11,P12,P19,P23). In the wake of increased environmental

Table 5
Theories that promote environmental sustainability.

Theory	Context	Participants
Lean	Continuous improvement philosophy	[5,6,8,12,14,15,17,18,19,20,24]
Project Management	Effective co-ordination of engineering and business activities	[5,9,11,14,16,17,20,21]
Simulation	Numerical stochastic modelling approach	[3,4,9,19,21,22,23]
Life cycle assessment & analysis	Measuring and mapping environmental impact from resource extraction until end of life	[3,7,11,14,16,22,24]
Optimisation	Analytical approach to solve complex problems	[5,8,17,23,24]
Six Sigma	Statistical quality control principle	[5,6,8,9,20,24]
Supply chain management	Co-ordinating and managing operations and logistics across	[3,11,12,19,23]
Biomimicry	Nature-inspired innovation	[3,5,7,14,16]
Systems theory	Interconnected perspective on problems	[4,17,19,22]
Theory of constraints	Continuous improvement principles for bottleneck identification	[12,17,18,20]
Problem solving methods	Creative problem solving applications	[2,9,17]
Value chain optimization	Value system improvement	[3,17,18]
Multi-level perspectives	Multidimensional feasibility domains	[5,9,12]
Quality management	Quality management principle	[6,9,22]
Systems engineering	Sub-system and system integration and improvement	[10,11,23]
Mathematics & Statistics	Subject matter	[10,17,24]
Management theory	Management sciences for ownership and decision making	[1,14]
Motivational theories	Leadership and workforce motivation artefacts	[1,17]
Financial management	Economic activities streamlined	[1,2]
Decarbonization	Reducing greenhouse gas emissions	[3,11]
Systems dynamics	High-abstraction simulation paradigm	[4,11]
Operational excellence	Continuous improvement principles owed to people management	[4,20]
Cradle to grave	Life cycle perspective	[4,20]
Artificial Intelligence	Disruptive technology to aid in decision making, ideation, creation and implementation	[6,14]
Operations management	Improving operations to be more efficient and sustainable	[10,22]
Leadership	Leading organisations	[10,14]
Product life cycle management	Product-centric focus across all product stages	[11,15]
Change management	Individual and organisation technique for radical or incremental changes	[17,20]
Design thinking	Mental artefact design methodology	[17,20]
Sustainable value chains	Product, process and technology value chains scaled for sustainable execution and longevity	[17,24]

Table 5 (continued)

Theory	Context	Participants
Facilities design	Layout design of production/service	[15,17]
Scenario planning & analysis	Foresight technique	[17,19]
Carbon footprinting	Measuring carbon equivalent and environmental impact	[3]
Nature based solutions	Nature-inspired solutions	[3]
Soft systems methodology	Problem solving approach for complex, hairball structured problems	[4]
Machine learning	Statistical learning technique	[6]
Sustainability resilience	Responsive and sustainable SCA approach	[9]
Renewable energy development	Cleaner technologies	[9]
Value engineering	Intangible and tangible value generation, capturing and improvement	[10]
Operations research	Optimisation specialisation	[10]
Managerial discretion	Management trade-off in individual and collection decision making	[10]
Boundary expansion	Systematically understanding broader impacts on organisations	[11]
Green growth	Sustainable strategic, employment and economic growth	[11]
Soft systems thinking	High abstraction form of systems thinking	[11]
Industrial ecology	Transdisciplinary concept for industrial and ecological symbiosis	[11]
CYNEFIN model	Complexity theory decision making framework	[14]
Future thinking	Foresight principles	[14]
Design For Environment	Product design for environmental preservation	[18]
Risk management	Risk assessment and mitigation strategies	[19]
Energy management	Efficient energy consumption	[22]
Industrial symbiosis	Dual gain across operational and environmental targets	[22]
Transition literature	Radical changes between unsustainable to sustainable socio-technical systems	[9]

and technological challenges, sustainable supply chain systems are the way forward [94].

All of the aforementioned forms of theory rally a strategic vision. The next cascading application stream calls on methods and practices embodying tools and techniques.

4.5. Methods and practices

Methods and practices are informed by the strategic vision and theory adoption in the organisation [30]. These are more technical and practical aspects that form part of daily operations at a tactical level. Table 6 outlines the various methods and practices mentioned during the interviews.

Table 6
Methods and practices that promote environmental sustainability.

Method or practice	Participants
ESG reporting	[1,2,5,7,11,12,22,23]
Data analysis	[8,12,17,19,22]
Recycling	[3,15,18,24]
3R, 6R, 12R	[3,6,19,21]
Value stream mapping	[15,17,18,20]
Linear programming	[4,10,17]
5S	[6,18,20]
Polluter pays principle	[7,10,14]
Carbon trading	[10,19,22]
Feasibility study	[3,21,24]
Benchmarking	[16,19,21]
Root cause analysis	[10,17,27]
Fishbone	[8,9,17]
Business strategic tools	[9,13,17]
Environmental audits	[2,24]
Carbon tax	[3,14]
Carbon capture	[3,7]
Linear programming	[10,17]
Legislation and policy	[3,10]
Material flow analysis	[11,14]
Standard operating procedures	[13,18]
Product design and regeneration	[14,16]
Supply chain optimization	[14,24]
Greenwashing	[19,24]
PROCI	[20,21]
Water and energy consumption	[7,22]
Workforce upskilling	[21,22]
PDCA	[17,20]
Current state analysis	[10,18]
Greenhouse gas protocols	[3]
Forecasting	[3]
Regression analysis	[3]
Software	[3]
Upcycling	[3]
Business process mapping	[4]
Scope emissions	[4]
KPI tree	[4]
Stakeholder analysis	[4]
Environmental monitoring	[5]
Standardization	[6]
Eco machines	[7]
SWOT analysis	[8]
SCRUM	[8]
Communication	[10]
11 GA outcomes for ECSA	[10]
Sound judgement	[10]
Waste reduction	[14]
Facility & process design	[14]
Work study	[15]
Net zero waste	[16]
Data visualization	[17]
Value chain optimization	[18]
Sensitivity analysis	[19]
5 Whys	[19]
Reverse logistics	[20]
FMEA	[21]
SIPOC diagrams	[21]
Load curtailment	[24]
New technology	[24]
Batch processing	[3]
Statistical analysis	[3]
Circular supply chain	[20]
Pareto Analysis	[9]
Critical thinking	[9]
DMAIC	[9]
Business process re-engineering	[17]
Ethical decision making	[10]
Intelligent manufacturing	[14]
ADKAR	[21]

4.5.1. R paradigm paradox

Recycling is often seen as a go-to method to reduce the environmental impact of an organisation [95]. However, it could do more harm to the environment than good (P3, P15). Although counterintuitive,

recycling is not always environmentally viable when increasing resource consumption [96], especially when the material movement and energy consumption supersedes the environmental gain (P19). This is especially the case with transport emissions [97]. According to participant 19, reverse logistics is so carbon-intensive that it may be more environmentally viable to pursue a new feedstock and develop new products instead. According to Fooks and Langford [98], it can consume 33 % more energy than non-recycled material. This means more creative recycling approaches or alternatives need to be carefully considered.

4.5.2. Batch processing and VSM

Batch processing can be seen as a rather unsuspecting approach since it disobeys the low inventory and one-piece flow principles of Lean (P6). Batch processing are advised when production activities are energy-intensive. Furthermore, they can be scheduled during renewable energy supply peak times (P3). Value stream mapping can establish the value stream, every process touch point for quality improvement and ES assessment within organisations and suppliers (P18). This is achieved by reducing non-value adding time and length of stay [99].

4.5.3. Human-centredness

More people-centred and humanistic traits emerged in the analysis. One was empathy. Participant 10 proclaimed that industrial engineers design with empathy and consideration, an attribute giving cognisance of the impact processes and systems have on the environment. Their design brings a user-centric perspective that ensures designs that are fit for people and not just for purpose. Another important human aspect is training and education. Participant 21 believes this would help change the perceptions, attitudes and cultures of employees and shift their mindset towards a greener approach to operations. This also preserves a resource-conservative approach that is passed on to future generations. This inculcates a sustainability culture amidst growing fixation on social sustainability for sustainable organisations [100]. This can be further strengthened by considering the stance indigenous knowledge holds on sustainability practices s [101].

4.5.4. Supply chain optimisation

By optimising eco-friendly materials in the supply chain, it can become more green (P24). Collaboration with various stakeholders is pivotal (P2). At times, stakeholder analysis can aid in addressing scope 3 emission concerns tied to supplier selections (P4).

For a SCA, the processes, influence, rehabilitation and entire life cycles are crucial (P14). Important considerations from participant 11 included degrowth and sunset technologies. Previously, manufacturers were able to innovate on behalf of the consumer, pushing products into the market with the hope of adoption. This very quickly proved unsustainable. The drive for competitiveness has moved the manufacturer closer to the supply chain and increased customer power (P11). For degrowth, the onus is on engineers to ensure new products and services have less consumption and the same, if not, greater value to society. From this, it can be argued that engineers should step outside their boundaries and assess the impact of the activities they manage and design for degrowth-oriented organisational value [102].

4.5.5. Measuring performance

Technology and software become underlying features to measure performance as a standard practice [103]. Only once you begin measuring, do targets become more tangible (P22). Some of the environmental performance measures can be achieved with more cohesiveness when linked with a balanced scorecard (P24). Any KPI must be continuously monitored. The metrics concerning nature and societal human well-being are the most important (P11). Using reliable data and methods of analysis, organisations can identify improvement opportunities (P12), which can be further supported using various software such as Python, R and Matlab (P3). Automated metering and advanced technologies can also create more human potential to address

organisational challenges and implement interventions that improve environmental performance (P3,P24). Data science and data engineering also resonate with environmentalism since environmental impact can be modelled through predictive analytics, similar to predictive maintenance (P22).

4.5.6. Legislation, policy and cleaner technologies

Legislation and policy are pertinent aspects that belong to the ES discussion. In South Africa, the South African National Standards (SANS) 17 000 and 20 000, are considered (P3). The Environmental Engagement Act and National Waters Act (P16) also provide policy suggestions on environmental disclosure compliance. ISO standards such as 14 000 (P24) and 9 001 (P22) ensure quality management practices are brought into action. Similar to ESG, GRI reporting, and the Taskforce on Nature-related Financial Disclosures promote a SCA (P3). Currently, institutions are making legislative changes which will take effect in the next two years. This perpetuates new policies that will impact manufacturing and agricultural sectors in developing countries since exports and other costs are likely to be altered (P22).

Policy and regulatory implementation exists at varied levels, the policy itself, organisational, governmental and community levels. An example of policy adaptations could be to configure circular supply chain employing reverse logistics (P20). Governments can work more closely with promulgated laws that discourage environmental degradation and indirectly promote sustainable operations. Within organisations, methods and practices can help formulate a SCA that is efficient and profitable for the organisation. Ultimately, this could have an impact on communities which can pursue community-owned practices in the WEF nexus. Communities can also create micro-economies and micro-network solutions that solve societal and economic issues simultaneously.

ES in the power industry is critical (P1). Cleaner technology-based energy generation use, and distribution can aid national grids (P20). In South Africa, energy demand amidst a lack of supply has resulted in loadshedding or rolling blackouts. This solution could be beneficial for the country, creating more stability in the already constrained power grid while creating additional organisational revenue. Another method to curb the undersupply of energy is through load curtailment, which creates grid stability by reducing peak energy usage (P24). Environmental policy is a trusted mechanism to accelerate cleaner technology diffusion, more so when incentivised [104].

The findings obtained in the interviews are now tied closer to the literature using Section 5.

5. Discussion of findings

The discussion will balance the interview findings with literature. An interviewee stated that the fields of IE and ES have been largely disconnected (P9). Another participant confessed that IE has a peculiarly low contribution towards ES (P11). In general, sustainability must be seen holistically to ensure meaningful organisational transformation. For an SCA, it must form part of the operations strategy (P1), corroborated by the research of Nunes et al. [105].

To operationalise the results, practitioners in South Africa can follow a top-down approach for implementation, although this is not universal [106]. Management can drive a top-down strategy using specific theories carried out by means of specific practices (P10). For instance, continuous improvement can be adopted as a strategy which turns to Lean as a theory when implementing value stream mapping (P6). These knowledge components can be used in conjunction with other frameworks and concepts within their problem-solving paradigm such as Action Design Research, Soft Systems methodology, TRIZ and more [107]. However, relationships and maturity levels across strategic, theoretical and practical facets must be scrutinised for knowledge component integration.

The term sustainability is broad, necessitating its decomposition into

more common terms (P15). Lutz Newton and Freyfogle [108] argue that it is overused and should be linked to other forms of classification. It has been reaffirmed that the economy, communities and society are embedded within the environment as an interconnected system (P11). The same can be said for technology. Technology that exists is “within the organization that is within economies within the society, is within the environment” (P12). A similar sentiment from Giddings et al. [109] is also shared. IE work lies outside its traditional manufacturing environment and extends into areas such as design processes and simulation (P3,P4,P9,P19,P21,P22,P23) and backed by Donald et al. [110]. Productivity goals concern complex adaptive systems in various industries (P9,P14). Moreover, the problems that exist in many of these industries in Africa are wicked [111]. Participant 17 believed all require complex problem-solving. IE finds the root cause of problems to prevent new environmental problems (P10), on a deep and systemic level [112].

For an SCA, adding sustainability transcends innovation (P5,P9,P11). ES needs to have innovation, management and technology management as part of the narrative (P9). According to Johannessen and Olsen [113], innovation is a catalyst for SCA within the knowledge economy. Currently, there is a lack of holism within existing business models, theories and frameworks (P9,P11,P13). There is an opportunity to embed sustainability traits in business models for innovation (P9,P13). A testament to this is the work of Averina et al. [114] who embed sustainability narratives to unlock the sustainability value. Participant 17 mentions how a business model canvas and other strategic tools aid in sustainability pursuits, but lack real environmental considerations. One can also embed sustainability in innovation approaches (P9), although it would require business models modifications similar to the work of Lüdeke-Freund et al. [115] who have developed sustainable shared value business models.

Stakeholder relationships must be maintained to best support a sustainability vision. Operations, simple quality measures and quality improvement approaches can be used to translate efficiency gains in environmental contexts (P9). A noteworthy attribute IE has is that they understand the skills needed to remain relevant, diversify offerings and remain competitive (P11).

Environmental practitioners often contain the most accurate longitudinal data to evaluate the impact of industrial activities (P14). ES efforts are seen as an additional cost to the organisation (P14). This sentiment is shared by Metz et al. [116] who argue that organisations see sustainability as a cost and not an opportunity for increasing competitive advantage and creating new business value. This means more specialised skills equipment is needed for quality control (P1). For example, ESG reporting becomes more costly with more resources needed to help monitor and manage reporting (P1,P2).

CE continues to revitalise innovation ecosystems through product design, business model strategies and circular supply chains [117–119]. CE has a major impact on maintenance by being able to reduce waste (P22). Synergy exists between CE and servitization (P22), as discussed in Section 4.2.2.

According to participants 12 and 17, if we incentivise decision-makers and stakeholders, we can prioritise environmental gains that share synergy with economic gains. With managerial discretion, the creation of a decision chain within organisations can drive actions as a product of individual-level decisions that create a cohesive strategy (P10), aligned throughout all organisational levels [120]. In manufacturing environments, we can incentivise the manufacturer and employ the polluter pays principle to ensure that cleaner production is pursued (P7).

Biomimicry was identified as a trustworthy form of theory to solve for ES (P3,P5,P7,P14,P16). Biomimicry is a design philosophy that was pioneered by Benyus [121] as a revolutionary science that abstracts, analyses and adapts nature's best ideas for human use. According to Barbinta-Patrascu et al. [122], it can address environmental challenges having a nature-inspired association since ecosystems and species have thrived for millions of years. Biomimicry is one path to sustainable

innovation, and hence a pathway to an SCA [123].

Industry 5.0 is a newly coined term that refers to the improvement of Industry 4.0 by still making use of highly advanced technologies to ensure societal wellbeing and environmental performance [124]. It focuses on human-centricity, sustainability and resiliency by creating a symbiotic ecosystem [125]. It is geared towards working with machines to aid humans, improve processes and ensure they are more efficient (P5,P14). According to Xu et al. [126], the use of Industry 5.0 leads to value generation that contributes to CE, CO₂ reduction, societal challenges being addressed, business models created and profitability for organisations.

Participant 14 contentiously argued that although the people, planet and profit are crucial, the planet is resilient. The participant further stated that we have a responsibility to people not to steer away from interacting with nature in fear of its collapse. This complements the discussion from Swain [127] regarding SDG pillars and advises that developing countries should focus on the economy and society before the environment. It is, however, important not to take this relationship for granted, and to be responsible for how we use the environment for economic and social prosperity. We need to protect societal well-being as much as the environment (P11). We should use indigenous knowledge systems and culture to ensure a sustainable solution that ensures social prosperity and protects the environment (P11). For a SCA, an innovation culture is needed [113]. Participant 19 shared a similar sentiment about the economy, stating that we need to ensure economic gain for society.

It stands to reason that IE can almost equate to Industrial Ecology (P11). Aforetime, Industrial Ecology has been explained using industrial symbiosis features extracted from industrial engineering analogies, showcasing that IE is a strong component of industrial ecology [128]. Participant 11 researched industrial symbiosis as a subset of industrial ecology where CE features, but they believe this is Industrial engineering in effect. Resource optimisation and facility design successes from Industrial Ecology are fundamental IE concepts [129,130].

Although the findings were found to explore South Africa, many developing countries share similar complex or wicked problems [111, 131]. It is for this reason that the findings relate to other countries that share similar societal and environmental challenges, given similar interest, action and competencies as seconded by Withycombe Keeler et al. [132]. The findings are also found to complement the work of Tsoku et al. [9] who identify the role of Industrial Engineering with sustainability using a systematic literature review, Roopa et al. [30] that evidence of the link between Industrial Engineering and Environmental Sustainability, and also the research from Machado et al. [133] which provides an overview of the relationship between Industrial Engineering, operations management and sustainability. These can also be scaled to other developing economies beyond South Africa.

6. Conclusions, limitations and future research

6.1. Concluding remarks and implications

Objective 1 sought to explore the relationship between IE and ES for an SCA. This moderately disconnected subset was deduced in Section 2 and further evidenced by existing IE and ES clusters. The next objective extracted knowledge components within transdisciplinary contexts, being the first to identify harmonious or hybrid IE and ES knowledge components for an SCA in South Africa. A total of 143 different knowledge components from IE and ES are presented in this paper based on 374 examples harnessed from 24 interviews.

To answer research question 1, the representation of this data boasts findings that achieve synergy between the previously disconnected paradigms that now showcase integrated, transdisciplinary knowledge. The interconnected knowledge components demonstrate that ES needs to be embedded into KPI selection, monitoring and analysis to establish a holistic understanding of the entire system. This endorses the

Industrial engineer as an appropriate member within organisations to lead ES and SCA initiatives with their creative solutions to complex problems, emphasised by the vast knowledge components obtained in this study.

When comparing the results with the existing body of literature (research question 2), sustainable strategies and needs will only become ever-present and more pertinent to organisations across all sectors. Hence, SCA will soon become a core concept that needs to be better understood. It requires more than just innovation, but management and technology considerations to be embraced within the organisation. The concept of Industry 5.0 is likely to become more popular in academia and industry. When problem-solving across supply chain contexts, closed-loop configurations and CE principles offer immense value in achieving an SCA by revitalising the supply chain, redesigning the business ecosystem and improving the life cycle. For the South African context, the strategies can be further adapted to accommodate the service economy, which sustains many business activities across various sectors in the country.

The implications of this research prompt industrial engineers to address ES issues and create transdisciplinary knowledge by integrating various forms of knowledge components. Different roles in various types of organisations can appreciate different forms of results across the strategic, tactical and operational business levels. These findings directly inform practitioners and academics on the forms of knowledge components for an SCA in South Africa.

The findings from the study speak to both the academic and the practitioner. For the academic, the continuous improvement approaches, strategies and theories would be of interest. Various methods and practices can generate empirical evidence for sustainability research. For the practitioner, the management approach, operational and tactical findings may be of more relevance since this delves more into measuring and improving operations with an SCA. Nonetheless, collectively, the findings guide management on strategic directions they can pursue to remain competitive. The findings appeal to various sectors in developing countries with the categorisation structured across cascading application streams within any organisation. It can also aid in policymaking since strategies can be aligned at the governmental level in policies and regulations, and international levels using protocols or SDG alignment. Policymakers can therefore conceptualise different policies across all knowledge components between SCA's that are sector specific, measurable and tied to societal impact along sustainability narratives.

6.2. Limitations

This research was limited to IE and ES and did not consider other knowledge components from other engineering disciplines or other sustainability dimensions. It can also be argued that the results are generalised for all sectors despite the transdisciplinary nature of the findings.

Another shortcoming is that the findings were limited to the discussions from the population interviewed. The study could have considered other engineering disciplines or individuals with less than four years of experience.

The exact modular arrangement of these findings and how they cascade was outside the scope of the study. The assortment of these knowledge components between the business execution levels remains unclear.

6.3. Future research

Mental artefacts (research products) will need to be developed as the way forward. Forthcoming research will need to map out the implications the knowledge components have with each other, their application stream, maturity levels in organisations or existing constructs from sustainability frameworks and models using various design approaches.

Interviews or literature reviews could explore sector or other regional-specific renditions of these findings against laws and country-specific environmental goals.

Further research can propose more robust mixed-method approaches, including quantitative modelling that complements qualitative insights on IE and ES research. Quantitative studies can also develop impact assessment, simulations, systems dynamics models or analytical models to evaluate and quantify the ES and SCA gains using these knowledge components. These could assess the different business execution levels or the various set of activities within organisations. Mixed methods studies can support this research with results or future-designed artefacts from the knowledge components in this research. Quantitative approaches can validate qualitative insights from applied literature reviews, interviews, questionnaires or exploratory focus groups on IE and ES research. Evaluations using surveys or confirmatory focus groups could generate ordinal data for statistical analysis. Furthermore, transdisciplinary research could provide the co-design, co-production and co-implementation research steps for various types of research.

Emergent and disruptive technologies will always impact sustainability narratives. Future research could explore how emerging technologies such as AI and IoT can foster IE and ES integration for a SCA at this sustainability interface.

Cultural aspects can also be explored and tailored to indigenous knowledge systems to synchronise with organisational SCA intent, or conducting research that explores cross-cultural comparisons to unlock universal and context-specific practices. Future studies can contextualise the findings, explore other sustainability dimensions and assess the policy and organisational impact these findings can have. Another research stream could explore ways IE can address other complex societal, economic or environmental issues through transdisciplinary knowledge creation by finding harmony with other realms of knowledge.

Ethical statement

This study was approved by the North-West University Research Ethics Committee on 1 November 2023 with the approval number: NWU-00235-23-A3.

Funding sources

This research had no funding sources.

Declaration of generative AI in scientific writing

The authors declare no generative AI use in the research.

CRediT authorship contribution statement

Meelan Roopa: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Raj Siriram:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare no competing interest.

Data availability

The data that has been used is confidential.

References

- [1] (IISE), Institute of Insutrial and Systems Engineering, IISE Body of Knowledge, 2021. <https://www.iise.org/Details.aspx?id=43631>.
- [2] G. Salvendy, Handbook of Industrial engineering: Technology and Operations Management, John Wiley & Sons, 2001.
- [3] H. Darwish, L. Van Dyk, The industrial engineering identity: from historic skills to modern values, duties, and roles, *S. Afr. J. Ind. Eng.* 27 (3) (2016) 50–63.
- [4] M. Mangaroo-Pillay, M. Roopa, Beyond the industrial engineering frontier: a few steps in history and a giant leap into the future, *S. Afr. J. Ind. Eng.* 32 (3) (2021) 1–9.
- [5] G.D. Catalano, Engineering, Poverty, and the Earth, Morgan & Claypool Publishers, 2007, p. 4.
- [6] Dahmus, J.B. & Gutowski, T.G. 2005. Efficiency and production: historical trends for seven industrial sectors. *In*.
- [7] H. Darwish, Expanding Industrial Thinking By Formalizing the Industrial Engineering Identity For the Knowledge Era, North-West University, 2018.
- [8] H. Schandl, M. Fischer-Kowalski, J. West, S. Giljum, M. Dittrich, N. Eisenmenger, A. Schaffartzik, Global material flows and resource productivity: forty years of evidence, *J. Ind. Ecol.* 22 (4) (2018) 827–838.
- [9] T. Tsoku, L. van Dyk, W. Maisiri, The role of industrial engineering and its impact on sustainability: a systematic review approach, *S. Afr. J. Ind. Eng.* 35 (3) (2024) 70–79.
- [10] R.M. Indriawati, E. Gravitani, A.M. Soesilo, M. Cahyadin, Long-term investigation of emissions and economic growth in developed and developing countries: a bibliometric analysis, *Int. J. Energy Econ. Policy* 13 (3) (2023) 219–234.
- [11] I.M. Ziaul, W. Shuwei, Environmental sustainability: a major component of sustainable development, *Int. J. Environ. Sustain. Soc. Sci.* 4 (3) (2023) 900–907.
- [12] C.N. Madu, A decision support framework for environmental planning in developing countries, *J. Environ. Plan. Manag.* 42 (1999) 287–313.
- [13] H. Sepehrdoust, S. Zamani, The challenge of economic growth and environmental protection in developing economies, *Iran Econ. Rev.* 21 (4) (2017) 865–883.
- [14] M. Dos Santos, Achieving sustainable competitive advantage through the implementation of the societal marketing concept by a major retailer in South Africa, *J. Glob. Bus. Technol.* 5 (2) (2009) 39.
- [15] F. Rattalino, Sustainability and competitive advantage: a case of patagonia's sustainability-driven innovation and shared value. *Handbook of Research On Business Ethics and Corporate Responsibilities*, IGI Global, 2015, pp. 330–355.
- [16] J.R. Bryson, R. Lombardi, Balancing product and process sustainability against business profitability: sustainability as a competitive strategy in the property development process, *Bus. Strategy. Environ.* 18 (2009) 97–107.
- [17] J. Bernstein, Transdisciplinarity: a review of its origins, development, and current issues, *J. Res. Pract.* 11 (2015) 1.
- [18] A. Dalton, K. Wolff, B. Bekker, Interdisciplinary research as a complicated system, *Int. J. Qual. Methods* 21 (2022) 16094069221100397, <https://doi.org/10.1177/16094069221100397>. <https://journals.sagepub.com/doi/abs/10.1177/16094069221100397>.
- [19] G. Tress, B. Tress, G. Fry, Clarifying integrative research concepts in landscape ecology, *Landsc. Ecol.* 20 (2005) 479–493.
- [20] C. Rigolot, Transdisciplinarity as a discipline and a way of being: complementarities and creative tensions, *Humanit. Soc. Sci. Commun.* 7 (1) (2020) 1–5.
- [21] M.A. Max-Neef, Foundations of transdisciplinarity, *Ecol. Econ.* 53 (1) (2005) 5–16.
- [22] R.D. Arnold, J.P. Wade, A definition of systems thinking: a systems approach, *Procedia Comput. Sci.* 44 (2015) 669–678.
- [23] B. Alessandro, C. Caterina, L. Marinella, R. Francesco, Z. Alessandro, Biomimicry thinking: methodological improvements and practical implementation, *Bioinspired. Biomim. Nanobiomater.* 6 (2) (2017) 87–101, <https://doi.org/10.1680/jbibn.16.00007>. <https://www.icervtuallibrary.com/doi/abs/10.1680/jbibn.16.00007>.
- [24] U. Kanchan, N. Kumar, A. Gupta, Green business-way to achieve globally sustainable competitive advantage, *J. Progress. Res. Soc. Sci.* 2 (2) (2015) 92–100.
- [25] L. Kvasničková Stanislavská, L. Pilař, M. Fridrich, R. Kvasnička, L. Pilařová, B. Afsar, M. Gorton, Sustainability reports: differences between developing and developed countries, *Front. Environ. Sci.* 11 (2023) 1085936.
- [26] S. Singh, R.P. Mohanty, S.K. Mangla, V. Agrawal, Critical success factors of additive manufacturing for higher sustainable competitive advantage in supply chains, *J. Clean. Prod.* 425 (2023) 138908, <https://doi.org/10.1016/j.jclepro.2023.138908>. <https://www.sciencedirect.com/science/article/pii/S0959652623030664>.
- [27] I.H. De Kock, Managing Technology Within the Context of Sustainability transitions: An integrated Framework, Stellenbosch University, Stellenbosch, 2020.
- [28] T. Machingura, O. Adetunji, C. Maware, The mediatory role of the environmental performance function within the lean-green manufacturing sustainability complex, *TQM J.* (2024).
- [29] J.K. Musango, A.C. Brent, A.M. Bassi, Modelling the transition towards a green economy in South Africa, *Technol. Forecast. Soc. Change* 87 (2014) 257–273, <https://doi.org/10.1016/j.techfore.2013.12.022>. <https://www.sciencedirect.com/science/article/pii/S0040162514000031>.
- [30] M. Roopa, R. Siriram, R. Coetzee, Exploring industrial engineering knowledge and environmental sustainability, *Sustainability* 16 (17) (2024) 7392. <https://www.mdpi.com/2071-1050/16/17/7392>.

- [31] E.M. Fox, Competition policy: the comparative advantage of developing countries, *Law Contemp. Probl.* 79 (4) (2016) 69–84.
- [32] K. Malterud, Systematic text condensation: a strategy for qualitative analysis, *Scand. J. Public Health* 40 (8) (2012) 795–805, <https://doi.org/10.1177/1403494812465030>.
- [33] Kando, N. 1999. Text structure analysis as a tool to make retrieved documents usable. In.
- [34] D.M. Buede, W.D. Miller, *The Engineering Design of systems: Models and Methods*, John Wiley & Sons, 2024.
- [35] D. Mebratu, Sustainability and sustainable development: historical and conceptual review, *Env. Impact. Assess. Rev.* 18 (6) (1998) 493–520.
- [36] R. Goodland, H. Daly, Environmental sustainability: universal and non-negotiable, *Ecol. Appl.* 6 (4) (1996) 1002–1017.
- [37] K.R. Haapala, F. Zhao, J. Camelio, J.W. Sutherland, S.J. Skerlos, D.A. Dornfeld, J. L. Rickli, A review of engineering research in sustainable manufacturing, *J. Manuf. Sci. Eng.* 135 (4) (2013), <https://doi.org/10.1115/1.4024040>. Date of access: 12/17/2025. 10.1115/1.4024040.
- [38] P.D. Jensen, L. Basson, M. Leach, Reinterpreting industrial ecology, *J. Ind. Ecol.* 15 (5) (2011) 680–692.
- [39] M.-L. Tseng, T.P.T. Tran, H.M. Ha, T.-D. Bui, M.K. Lim, Sustainable industrial and operation engineering trends and challenges toward industry 4.0: a data driven analysis, *J. Ind. Prod. Eng.* 38 (8) (2021) 581–598.
- [40] S. Luthra, V. Kumar, S. Kumar, A. Haleem, Barriers to implement green supply chain management in automobile industry using interpretive structural modeling technique: an Indian perspective, *J. Ind. Eng. Manag.* 4 (2) (2011) 231–257.
- [41] M. Hossain, R. Al Aziz, C.L. Karmaker, B. Debnath, A.M. Bari, A.R.M.T. Islam, Exploring the barriers to implement industrial symbiosis in the apparel manufacturing industry: implications for sustainable development, *Heliyon* 10 (13) (2024).
- [42] V.K. Mittal, K.S. Sangwan, Prioritizing barriers to green manufacturing: environmental, social and economic perspectives, *Procedia CIRP.* 17 (2014) 559–564.
- [43] E.M. Goldratt, J. Cox, *The goal: a Process of Ongoing Improvement*, Routledge, 2016.
- [44] Q. Zhu, J. Sarkis, Y. Geng, Green supply chain management in China: pressures, practices and performance, *Int. J. Oper. Prod. Manag.* 25 (5) (2005) 449–468.
- [45] F. Hermundsdottir, A. Aspelund, Sustainability innovations and firm competitiveness: a review, *J. Clean. Prod.* 280 (2021) 124715, <https://doi.org/10.1016/j.jclepro.2020.124715>. <https://www.sciencedirect.com/science/article/pii/S0959652620347594>.
- [46] K.P. Coyne, Sustainable competitive advantage—what it is, what it isn't, *Bus. Horiz.* 29 (1) (1986) 54–61.
- [47] R. Sharma, H. Gupta, Harmonizing sustainability in industry 5.0 era: transformative strategies for cleaner production and sustainable competitive advantage, *J. Clean. Prod.* 445 (2024) 141118.
- [48] P. Tiwari, J.K. Sadeghi, C. Esono, A sustainable lean production framework with a case implementation: practice-based view theory, *J. Clean. Prod.* 277 (2020) 123078.
- [49] M. Waqas, X. Honggang, N. Ahmad, S.A.R. Khan, M. Iqbal, Big data analytics as a roadmap towards green innovation, competitive advantage and environmental performance, *J. Clean. Prod.* 323 (2021) 128998, <https://doi.org/10.1016/j.jclepro.2021.128998>. <https://www.sciencedirect.com/science/article/pii/S0959652621031887>.
- [50] S.K. Singh, A.N. El-Kassar, Role of big data analytics in developing sustainable capabilities, *J. Clean. Prod.* 213 (2019) 1264–1273, <https://doi.org/10.1016/j.jclepro.2018.12.199>. <https://www.sciencedirect.com/science/article/pii/S0959652618339155>.
- [51] F.W. Geels, Socio-technical transitions to sustainability: a review of criticisms and elaborations of the multi-level perspective, *Curr. Opin. Env. Sustain.* 39 (2019) 187–201, <https://doi.org/10.1016/j.cosust.2019.06.009>. <https://www.sciencedirect.com/science/article/pii/S1877343519300375>.
- [52] M.P. Mangaliso, Building competitive advantage from Ubuntu: management lessons from South Africa, *Acad. Manag. Perspect.* 15 (3) (2001) 23–33.
- [53] A.M. Gonyora, S. Migiro, B. Ngwenya, P. Mashau, Investigating open innovation strategic alignment for sustainable competitive advantage in the automotive supply chain in South Africa, *J. Transp. Supply Chain Manag.* 15 (2021) 554.
- [54] C. Willig, *EBOOK: Introducing Qualitative Research in Psychology*, McGraw-hill education, (UK), 2013.
- [55] Derkachenko, A. & Kononiuk, A. 2021. The application of the foresight maturity model (FMM) in a manufacturing company.
- [56] G. Schmidt, W.E. Wilhelm, Strategic, tactical and operational decisions in multi-national logistics networks: a review and discussion of modelling issues, *Int. J. Prod. Res.* 38 (2000) 1501–1523.
- [57] R.J. Harrington, M.C. Ottenbacher, Decision-making tactics and contextual features: strategic, tactical and operational implications, *Int. J. Hosp. Tour Adm.* 10 (1) (2009) 25–43.
- [58] H. Mintzberg, D. Raisinghani, A. Theoret, The structure of "unstructured" decision processes, *Adm. Sci. Q.* (1976) 246–275.
- [59] M.P. Petkov, L.G. Kaoullas, Overcoming respondent resistance at elite interviews using an intermediary, *Qual. Res.* 16 (4) (2016) 411–429.
- [60] W.M. Trochim, J.P. Donnelly, *Research Methods Knowledge Base*, Atomic dog publishing, Cincinnati, OH, 2001, p. 2.
- [61] Atkinson, R., Flint, J. & John. Accessing hidden and hard-to-reach populations: snowball research strategies. In.
- [62] C. Noy, Sampling knowledge: the hermeneutics of snowball sampling in qualitative research, *Int. J. Soc. Res. Methodol.* 11 (4) (2008) 327–344.
- [63] H.A. Qureshi, Theoretical sampling in qualitative research: a multi-layered nested sampling scheme, *Int. J. Contemp. Res. Rev.* 9 (8) (2018) 20218–20222.
- [64] J.W. Creswell, J.D. Creswell, *Research design: Qualitative, quantitative, and Mixed Methods Approaches*, Sage Publications, 2017.
- [65] S.C. Weller, B.N. Vickers, H.R. Bernard, A. Blackburn, S.P. Borgatti, C.C. Gravlee, J.C. Johnson, Open-ended interview questions and saturation, *PLoS. One* (2018) 13.
- [66] G. Guest, A. Bunce, L. Johnson, How many interviews are enough? an experiment with data saturation and variability, *Field. Methods* 18 (1) (2006) 59–82.
- [67] O.C. Robinson, Probing in qualitative research interviews: theory and practice, *Qual. Res. Psychol.* 20 (3) (2023) 382–397.
- [68] T.J. Thorsteinson, A meta-analysis of interview length on reliability and validity, *J. Occup. Organ. Psychol.* 91 (1) (2018) 1–32, <https://doi.org/10.1111/joop.12186>. <https://bpspsychub.onlinelibrary.wiley.com/doi/abs/10.1111/joop.12186>.
- [69] H.I. Brink, Validity and reliability in qualitative research, *Curriculum* 16 (2) (1993) 35–38.
- [70] L.S. Wrightsman, S.W. Cook, C. Sellitz, *Research Methods in Social Relations*, Holt, Rinehart and Winston, 1976.
- [71] M.D. LeCompte, J.P. Goetz, Problems of reliability and validity in ethnographic research, *Rev. Educ. Res.* 52 (1) (1982) 31–60.
- [72] J.J. Francis, M. Johnston, C. Robertson, L. Glidewell, V. Entwistle, M.P. Eccles, J. M. Grimshaw, What is an adequate sample size? operationalising data saturation for theory-based interview studies, *Psychol. Health* 25 (10) (2010) 1229–1245, <https://doi.org/10.1080/08870440903194015>, 10.1080/08870440903194015.
- [73] K. Charmaz, *Constructing grounded theory*, Sage (2014).
- [74] H. Alshenqeti, Interviewing as a data collection method: a critical review, *Engl. Linguist. Res.* 3 (1) (2014) 39–45.
- [75] V. Clarke, V. Braun, Thematic analysis, *J. Posit. Psychol.* 12 (3) (2017) 297–298, <https://doi.org/10.1080/17439760.2016.1262613>, 10.1080/17439760.2016.1262613.
- [76] M.I. Alhojailan, M. Ibrahim, Thematic analysis: a critical review of its process and evaluation, *West East J. Soc. Sci.* 1 (1) (2012) 39–47.
- [77] A. Castleberry, A. Nolen, Thematic analysis of qualitative research data: is it as easy as it sounds? *Curr. Pharm. Teach. Learn.* 10 (6) (2018) 807–815, <https://doi.org/10.1016/j.cptl.2018.03.019>. <https://www.sciencedirect.com/science/article/pii/S1877129717300606>.
- [78] A. De Vos, H. Strydom, C.B. Fouche, C. Delport, *Research At Grass roots: For the Social Sciences and Human Service Professions*, Van Schaik, Pretoria, 2011.
- [79] C. Scheel, E. Aguinaga, A systems view of circular economy, *Sustainability* 17 (3) (2025) 1268. <https://www.mdpi.com/2071-1050/17/3/1268>.
- [80] R. Siriram, C.D. Plessis, A systems thinking approach to improving firms' competitive capabilities and firm performance, *Syst. Pract. Action. Res.* 37 (6) (2024) 1241–1280.
- [81] R. Siriram, Factors affecting the adoption of systems thinking, *Syst. Res. Behav. Sci.* 37 (2) (2020) 235–254.
- [82] G. Garcia-Garcia, G. Coulthard, S. Jagtap, M. Afy-Shararah, J. Patsavellas, K. Salonitis, Business process re-engineering to digitalise quality control checks for reducing physical waste and resource use in a food company, *Sustainability* 13 (22) (2021) 12341. <https://www.mdpi.com/2071-1050/13/22/12341>.
- [83] W.R. Stahel, The service economy: 'wealth without resource consumption'? *Philos. Trans. R. Soc. Math Phys. Eng. Sci.* 355 (1728) (1997) 1309–1319, <https://doi.org/10.1098/rsta.1997.0058>. Date of access: 12/14/2025. 10.1098/rsta.1997.0058.
- [84] F.J. Buera, J.P. Kaboski, The rise of the service economy, *Am. Econ. Rev.* 102 (6) (2012) 2540–2569.
- [85] L. Richter, M.Q. Khatib, Circular economy and ecologically sustainable behaviour in the light of financial constraints: quantitative results from Austria, *Front. Sustain.* 6 (2025) 1570573.
- [86] D. Schuler, A. Rasche, D. Etzion, L. Newton, Guest editors' introduction: corporate sustainability management and environmental ethics, *Bus. Ethics Q.* 27 (2) (2017) 213–237.
- [87] S. Shalev-Shwartz, S. Ben-David, *Understanding Machine Learning: From theory to Algorithms*, Cambridge university press, 2014.
- [88] J. Sathaye, O. Lucon, A. Rahman, J.M. Christensen, F. Denton, J. Fujino, A. Schaefer, Renewable energy in the context of sustainable development. IPCC Special Report On Renewable Energy Sources and Climate Change Mitigation, University Press, Cambridge, 2011.
- [89] J. Voorthuis, C. Gijbels, A fair accord: cradle to cradle as a design theory measured against john rawls' theory of justice and immanuel kant's categorical imperative, *Sustainability* 2 (1) (2010) 371–382. <https://www.mdpi.com/2071-1050/2/1/371>.
- [90] K. Zokaei, H. Lovins, A. Wood, P. Hines, *Creating a Lean and Green Business system: Techniques For Improving Profits and Sustainability*, CRC press, 2013.
- [91] M.J. Neubert, B. Dyck, Developing sustainable management theory: goal-setting theory based in virtue, *Manage Decis.* 54 (2) (2016) 304–320, <https://doi.org/10.1108/MD-05-2014-0312>. Date of access: 12/27/2025. 10.1108/MD-05-2014-0312.
- [92] J. Heilala, M. Paju, J. Montonen, R. Ruusu, M. Sorli, A. Armijo, S. Quintana, Discrete part manufacturing energy efficiency improvements with modelling and simulation, in: C. Emmanouilidis, M. Taisch, D. Kiritis (Eds.), *Advances in Production Management Systems. Competitive Manufacturing For Innovative Products and Services*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013, pp. 142–150.
- [93] D. Neumann, L.A. de Santa-Eulalia, E. Zahn, Towards a theory of collaborative systems, in: L.M. Camarinha-Matos, A. Pereira-Klen, H. Afsarmanesh (Eds.),

- Adaptation and Value Creating Collaborative Networks, Springer Berlin Heidelberg, Berlin, Heidelberg, 2011, pp. 306–313.
- [94] B. Beamon, Sustainability and the future of supply chain management, *Oper. Supply Chain Manag. Int. J.* 1 (1) (2014) 15.
- [95] Y. Virtanen, S. Nilsson, *Environmental Impacts of Waste Paper Recycling*, Routledge, 2013.
- [96] J.R. Catlin, Y. Wang, Recycling gone bad: when the option to recycle increases resource consumption, *J. Consum. Psychol.* 23 (1) (2013) 122–127.
- [97] B. Madden, N. Florin, S. Mohr, D. Giurco, Estimating emissions from household organic waste collection and transportation: the case of Sydney and surrounding areas, Australia, *Clean. Waste Syst.* 2 (2022) 100013.
- [98] J.R. Fooks, C.H. Langford, Paper recycling energetics: some Canadian experience, *Environ. Lett.* 6 (3) (1974) 205–210.
- [99] M. Nowak, H. Pfaff, U. Karbach, Does value stream mapping affect the structure, process, and outcome quality in care facilities? a systematic review, *Syst. Rev.* 6 (1) (2017) 170.
- [100] J. Pfeffer, Building sustainable organizations: the human factor, *Acad. Manage. Perspect.* 24 (1) (2010) 34–45.
- [101] A. Das, T. Halder, Indigenous knowledge helps to develop sustainable lifestyle practices, *Shanlax. Int. J. Educ.* 13 (3) (2025) 20–27.
- [102] T. Froese, M. Richter, F. Hofmann, F. Lüdeke-Freund, Degrowth-oriented organisational value creation: a systematic literature review of case studies, *Ecol. Econ.* 207 (2023) 107765, <https://doi.org/10.1016/j.ecolecon.2023.107765>, <https://www.sciencedirect.com/science/article/pii/S0921800923000289>.
- [103] R.I. Obi, Leveraging technology and data analytics in performance management—an exploratory study on its evolution: the when, now, and hereafter, in: ARPHA Conference Abstracts, Pensoft Publishers, 2024 e129581.
- [104] Vollebergh, H.R. 2007. Differential impact of environmental policy instruments on technological change: a review of the empirical literature.
- [105] B. Nunes, D.J. Bennett, D. Shaw, Building a Competitive Advantage Through Sustainable Operations Strategy, 2013.
- [106] J. Cairns Jr, Integrating top-down/bottom-up sustainability strategies: an ethical challenge, *Ethics Sci. Environ. Polit.* 3 (2003) 1–6.
- [107] E. Lodgaard, N. Iakymenko, M.F. Mogos, Toyota Kata for continuous improvement; an action research project in the construction industry, *Int. J. Lean. Six Sigma* 14 (6) (2023) 1264–1279.
- [108] J. Lutz Newton, E.T. Freyfogle, Sustainability: a dissent, *Conserv. Biol.* 19 (1) (2005) 23–32.
- [109] B. Giddings, B. Hopwood, G. O'Brien, Environment, economy and society: fitting them together into sustainable development, *Sustain. Dev.* 10 (4) (2002) 187–196.
- [110] D.L. Donald, N. Andreou, J. Abell, R.J. Schreiber, The new design: the changing role of industrial engineers in the design process through the use of simulation, in: WSC'99. 1999 Winter Simulation Conference Proceedings. 'Simulation - A Bridge to the Future' (Cat. No.99CH37038) 821, 1999, pp. 829–833.
- [111] V.-P. Niskanen, M. Rask, H. Raisio, Wicked problems in Africa: a systematic literature review, *Sage Open.* 11 (3) (2021) 21582440211032163.
- [112] E.D. Arnheiter, J.E. Greenland, Looking for root cause: a comparative analysis, *Tqm. J.* 20 (2008) 18–30.
- [113] J.A. Johannessen, B. Olsen, Systemic knowledge processes, innovation and sustainable competitive advantages, *Kybernetes* 38 (3/4) (2009) 559–580.
- [114] E. Averina, J. Frishammar, V. Parida, Assessing sustainability opportunities for circular business models, *Bus. Strategy. Environ.* 31 (4) (2022) 1464–1487.
- [115] F. Lüdeke-Freund, L. Massa, N. Bocken, A. Brent, J. Musango, Business models for shared value, *Netw. Bus. Sustain. S. Afr.* (2016) 1–98.
- [116] P.D. Metz, S. Burek, T.R. Hultgren, S. Kogan, L. Schwartz, The path to sustainability-driven innovation, *Res. Technol. Manag.* 59 (2016) 50–61.
- [117] N.M. Bocken, I. De Pauw, C. Bakker, B. Van Der Grinten, Product design and business model strategies for a circular economy, *J. Ind. Prod. Eng.* 33 (5) (2016) 308–320.
- [118] K. Govindan, M. Hasanagic, A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective, *Int. J. Prod. Res.* 56 (1–2) (2018) 278–311.
- [119] J. Konietzko, N. Bocken, E.J. Hultink, Circular ecosystem innovation: an initial set of principles, *J. Clean. Prod.* 253 (2020) 119942.
- [120] S. Finkelstein, D.C. Hambrick, Top-management-team tenure and organizational outcomes: the moderating role of managerial discretion, *Adm. Sci. Q.* 35 (1990) 484–503.
- [121] J.M. Benyus, *Biomimicry: Innovation inspired By Nature*, Morrow, New York, 1997.
- [122] M.-E. Barbinta-Patrascu, B. Bitu, I. Negut, From nature to technology: exploring the potential of plant-based materials and modified plants in biomimetics, bionics, and green innovations, *Biomimetics* 9 (7) (2024) 390.
- [123] E. Kennedy, D. Fechey-Lippens, B.-K. Hsiung, P.H. Niewiarowski, M. Kolodziej, Biomimicry: a path to sustainable innovation, *Des. Issues* 31 (3) (2015) 66–73.
- [124] S. Grabowska, S. Saniuk, B. Gajdzik, Industry 5.0: improving humanization and sustainability of industry 4.0, *Scientometrics* 127 (6) (2022) 3117–3144.
- [125] J. Leng, W. Sha, B. Wang, P. Zheng, C. Zhuang, Q. Liu, L. Wang, Industry 5.0: prospect and retrospect, *J. Manuf. Syst.* 65 (2022) 279–295.
- [126] X. Xu, Y. Lu, B. Vogel-Heuser, L. Wang, Industry 4.0 and industry 5.0—inception, conception and perception, *J. Manuf. Syst.* 61 (2021) 530–535, <https://doi.org/10.1016/j.jmsy.2021.10.006>, <https://www.sciencedirect.com/science/article/pii/S0278612521002119>.
- [127] R.B. Swain, A critical analysis of the sustainable development goals. *Handbook of Sustainability Science and Research*, 2018, pp. 341–355.
- [128] T.E. Graedel, On the concept of industrial ecology, *Annu. Rev. Energy Environ.* 21 (1) (1996) 69–98.
- [129] N.B. Jacobsen, Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects, *J. Ind. Ecol.* 10 (1–2) (2006) 239–255.
- [130] J.S. Mulrow, S. Derrible, W.S. Ashton, S.S. Chopra, Industrial symbiosis at the facility scale, *J. Ind. Ecol.* 21 (3) (2017) 559–571.
- [131] Sheng, T.Y., Li, E., Bruwer, J., Amin Mahir Abdullah, A.M.A., Brindal, M., Alias Radam, A.R., Suryani Darham, S.D. 2017. Factors influencing the adoption of sustainable agricultural practices in developing countries: a review.
- [132] L. Withycombe Keeler, F.D. Beaudoin, A.M. Lerner, B. John, R. Beecroft, K. Tamm, D.J. Lang, Transferring sustainability solutions across contexts through city–university partnerships, *Sustainability* 10 (9) (2018) 2966.
- [133] C.G. Machado, S.E.G. Da Costa, P.M. Manfrim, E.P. De Lima, Industrial engineering, operations management and sustainability: overview, *Braz. J. Oper. Prod. Manag.* 9 (2) (2012) 51–74.

Meelan Roopa is a PhD student in Industrial Engineering at North-West University and lecturer at the Department of Industrial Engineering at Stellenbosch University. His research interests entail Industrial Engineering, Environmental Sustainability, Biomimicry, Gamification, Business Engineering. He lectures Enterprise Design and Sustainable Logistics Systems.

Dr. Rajenlall Siriram is the CEO of Alpha Concepts, a consulting company on strategic planning. His research explores Technology, Innovation, Project management and Systems Thinking by employing a myriad of qualitative, quantitative and mixed-method techniques.

Chapter 6

6 An Industrial engineering lighthouse model for transdisciplinary problem solving and sustainable development in South Africa

This chapter serves as a conference paper **published and presented** at the SAIE 34 Illuminate Conference held in Vanderbijlpark, South Africa.

Title: An Industrial engineering lighthouse model for transdisciplinary problem solving and sustainable development in South Africa

Abstract: The industrial engineering profession is a prevalent multidisciplinary profession capable of yielding operational gains for organisations in almost any sector. However, it is unclear how the characteristics of this profession can be used to meet sustainability needs and complex problems in South Africa. This research presents an industrial engineering lighthouse model for strategic foresight in transdisciplinary problem solving in relation to the United Nations Sustainable Development Goals. This discussion paper reflects on existing literature as a basis for this novel artefact. Using the components that belong to this lighthouse, researchers and practitioners can identify future contributions Industrial Engineers can make in developing countries such as South Africa.

Keywords: Industrial Engineering; Foresight model; Sustainable Development Goals; Transdisciplinary research; South Africa

Doi: <https://doi.org/10.52202/078172-0014>

Introduction: Chapter 6 reproduces a single-authored conference paper presented at the SAIE 34 Illuminate Conference and marks the first attempt at artefact construction, rather than literature synthesis or empirical data collection using a methodology created. The chapter opens by restating IE's multidisciplinary character and its capacity to yield operational gains across almost any sector, before turning to the specific and considerable array of complex, "wicked" problems facing South Africa, including poverty, inequality, unemployment, landlessness, inadequate healthcare, food insecurity, and resource constraints. These are further characterised using the VUCA framing (volatility, uncertainty, complexity and ambiguity), which the chapter uses to argue that South Africa's development challenges, sustainable development chief among them, cannot be resolved through narrow, single-discipline interventions and instead demand a genuinely transdisciplinary (TD) response. IE is positioned as a plausible beacon of light for this task precisely because of its inherent multidisciplinary, systems-thinking orientation, and its established habit of drawing solutions from a wide array of theoretical domains.

The literature review that follows revisits the disciplinary-to-transdisciplinary spectrum (disciplinary, multidisciplinary, interdisciplinary, transdisciplinary) introduced in Chapter 2, and situates industrial ecology as an existing transdisciplinary field closely aligned with IE's own instincts. It then introduces two further conceptual building blocks unique to this chapter: strategic foresight and future cones, drawing on revised future cone models. This argues that structured anticipation of multiple possible futures is a necessary companion to transdisciplinary problem-solving, and the United Nations' seventeen Sustainable Development Goals (SDGs), which are presented as the substantive target that any South African TD problem-solving artefact should ultimately be designed to serve.

Relevant research component: Chapter 6 departs from the explicit research-question format used elsewhere in the thesis and instead states its problem, opportunity and aim directly. The research problem is that South Africa is confronted with complex problems and challenges, including sustainable development, that resist conventional solution approaches. The research opportunity identified is that industrial engineering can solve complex problems and sustainable development issues using transdisciplinarity, that is, the multidisciplinary foundation IE positions it well to lead TD problem-solving efforts if a suitable method and artefact can be developed. The research aim, correspondingly, is to develop an artefact that will facilitate transdisciplinary problem-solving and sustainable development in South Africa. Unlike Chapters 4, 5 and 9, Chapter 6 does not pose a discrete testable research question; rather, its logic proceeds directly from problem to opportunity to the design of a tangible artefact, the lighthouse model itself, that operationalises the opportunity identified.

Methodology: Chapter 6 introduces the Abstract-Contextualise-Design (ACD) methodology, a novel, exploratory, constructivist-paradigm design approach that becomes one of the thesis's most consequential methodological contributions, since it is subsequently adopted and extended in Chapter 7. The ACD methodology comprises three sequential stages. In the Abstract stage, the researcher selects a symbol, metaphor or icon that inspires the artefact and extracts "solution fragments" from it; here, a lighthouse is chosen for its associations with clarity, direction and guidance. In the

Contextualise stage, case-specific literature relevant to the problem and geography, in this instance, prior South African Industrial Engineering research artefacts, is gathered and summarised in tabular form (author, artefact, rationale, and design consideration) to inform the design that follows. In the Design stage, the solution fragments harvested from both prior stages are assembled into the finished artefact.

For this chapter, the contextualisation phase draws on seven prior South African IE studies, including the work of Darwish and Van Dyk (2016) on the industrial engineering identity tree, Mangaroo-Pillay Mangaroo-Pillay (2022) concerning the Lean-Ubuntu framework, Botha Botha (2018) on Industry 4.0 readiness model, and research from De Kock and Brent (2022) exploring socio-technical transitions linkage analysis. Each aspect contributes specific design considerations (balance, collectivism, future-readiness, innovation and multi-level perspective, respectively) that are explicitly carried into the final design. Unlike Chapters 4 and 5, no primary empirical data (surveys or interviews) is collected in this chapter; the methodology is entirely literature- and design-based, reflecting the nature of the chapter as a conceptual, artefact-first contribution rather than an empirical study.

Core findings: The chapter's principal output is the Industrial Engineering lighthouse model itself, a three-dimensional design that abstracts the physical mechanisms of a real lighthouse (lens, turntable, base, and clockwork mechanism) into a metaphorical structure for TD problem-solving. The model's five-sided theoretical base represents core IE knowledge domains (technology management, human factors engineering, operations research, engineering economics and operations management), while its clockwork core embodies the attributes most consistently recurring across the seven contextualising papers: stakeholder engagement, co-creation, collaboration, problem analysis, and impact assessment. The rotating light mechanism itself is structured around a four-stage backcasting process, formulating guiding principles, analysing the present situation, identifying leverage-point interventions, and experimenting strategically with those interventions, explicitly adapted from the four backcasting steps proposed in the literature. In total, 28 discrete solution fragments drawn from the contextualising literature were consolidated into the finished model.

The chapter frames the model implications primarily in terms of guidance rather than prescription. Given that the model is deliberately generic, it is intended to help researchers and practitioners identify a range of possible solutions appropriate to a specific problem, rather than dictating a single fixed pathway, an approach explicitly justified by reference wicked problems being best addressed with a range of possible solutions rather than one correct answer. The chapter closes by explicitly linking the lighthouse model back to the SDGs and, more ambitiously, to the African Union's Agenda 2063 goals, arguing that the model's core components could in principle be adapted to serve either framework, and by proposing that future work cascade the model's outputs further down the "knowledge supply chain" toward the Quadruple Helix of academia, industry, government and civil society.

Reflections: Chapter 6 is best understood as a proof-of-concept for the ACD methodology rather than as a definitive artefact in its own right. This is declared transparently by explicitly naming its own genericity (unspecific to any sector or industry) and its untested applicability beyond South Africa as limitations. This openly invites a reformulation of specific industries as future work. This degree of self-awareness is a strength rather than a weakness in the context of the wider thesis, since it establishes, quite deliberately, that the lighthouse model is a methodological rehearsal rather than the thesis's final artefact. The lighthouse metaphor itself is a distinctive and memorable design choice, closing, notably, with a literary allusion to Dumbledore's "turn on the light" quotation from the Harry Potter novels, a choice that signals the chapter's willingness to draw creative inspiration from outside strictly academic or engineering sources, consistent with the transdisciplinary ethos the whole thesis argues for.

Critically, however, Chapter 6's greatest methodological contribution is not the lighthouse model itself, but the ACD methodology it introduces and demonstrates for the first time. The three-stage Abstract-Contextualise-Design structure proves sufficiently robust and generalisable that it is picked up, essentially unchanged in its underlying logic, as the backbone of Chapter 7's much larger and more consequential TD framework. It becomes a mechanism or approach that is able to render a TD artefact. Read with hindsight, Chapter 6 therefore functions less as a standalone empirical contribution and more as a methodological pilot study whose real value is demonstrated retrospectively.

Inter-relationships across other chapters: The most significant relationship to the rest of the thesis is methodological rather than substantive: it is the origin point of the ACD (Abstract-Contextualise-Design) methodology that Chapter 7 explicitly adapts, cites, and extends. Chapter 6 shares its underlying transdisciplinary framing, and its use of the disciplinary-multidisciplinary-interdisciplinary-transdisciplinary spectrum, directly with Chapter 2's literature review and Chapter 3's research design chapter, both rely on the framework reproduced. Finally, Chapter 6's explicit engagement with the Sustainable Development Goals anticipates their reappearance as a formal evaluative framework in the Use Case Analysis in Chapter 9, where SDG alignment becomes one of the principal criteria against which the thesis's final artefact is assessed.

AN INDUSTRIAL ENGINEERING LIGHTHOUSE MODEL FOR TRANSDISCIPLINARY PROBLEM SOLVING AND SUSTAINABLE DEVELOPMENT IN SOUTH AFRICA

M.Roopa^{1*}

¹Department of Industrial Engineering
Stellenbosch University, South Africa
meelanroopa@sun.ac.za

ABSTRACT

The Industrial Engineering profession is a prevalent multidisciplinary profession capable of yielding operational gains for organisations in almost any sector. However, it is unclear how the characteristics of this profession can be used to meet the sustainable needs and complex problems in South Africa. This research presents an Industrial Engineering lighthouse model for strategic foresight in transdisciplinary problem solving in relation to the United Nations Sustainable Development Goals. This discussion paper reflects on existing literature as a basis for this novel artefact. Using the components that belong to this lighthouse, researchers and practitioners can identify future contributions Industrial Engineers can make in developing countries such as South Africa.

Keywords: Industrial Engineering, Foresight model, Sustainable Development Goals, Transdisciplinary research, South Africa

* Corresponding Author

1 INTRODUCTION

1.1 Background

Much like all engineering disciplines, engineers can produce value through innovative solutions that benefit society and communities at large. This notion cannot be more accurate for the industrial engineering discipline. The industrial engineering profession has emerged as an influencing engineering discipline that can yield productivity gains in various industries using a blend of mathematics, statistics, operations research, human factors engineering, psychology, management systems, economics, accounting and manufacturing systems engineering [1].

The multidisciplinary nature of the profession underscores the contribution it can make in solving the vast and rather complex array of challenges South Africa faces. According to Schutte, et al. [2], industrial engineering is responsive to technology trends and societal trends. This is also further supported by Mangaroo-Pillay and Roopa [3], believing that the profession will start to embark on new problem-solving ventures that belong to social sciences and environmental studies. South Africa is bombarded with several issues which relate to other developing countries.

In South Africa, problems are ever-present, and challenging and lead to excessive resource allocations with growing concern. According to Smith [4] and Legotlo [5], South Africa is confronted with issues concerning widespread poverty, inequality, unemployment, landlessness, homelessness, lack of basic services, lack of adequate healthcare, food insecurity, constrained resources, corruption, poor education systems and high levels of crime and violence.

Authors have provided innovative descriptions of problems that we face. One such example is to describe problems as “wicked”. Wicked problems are seen as complex, contested and unique social and socio-ecological issues that relate to various stakeholders with changing requirements [6, 7]. There exists no “silver bullet” to resolve wicked problems [8]. Another categorisation of problems is housed in what we now see as a VUCA world. VUCA is viewed as a world or environment where problems possess volatility, uncertainty, complexity and ambiguity [9]. According to Dhillon and Nguyen [10], we are all agents in a VUCA environment. Problems are sporadic, systemic, ever-changing and ill-defined with hairball structure ultimately resulting in vague perceptions and no clear nexus.

Problems in society often relate to the challenge of sustainable development. All developing countries have a more complicated path to sustainable development; hence South Africa is not alone in the pursuit for transformative changes in society [11]. The nature of problems that pertain to sustainable development require a multidisciplinary approach [12]. The industrial engineering profession may be the beacon of light that can solve these complex problems since it inherently is multidisciplinary and harnesses solutions from a vast array of theory domains that produce integrated knowledge. The industrial engineering profession can illuminate and uncover new root causes behind problems, employ systems thinking, and project new solutions to produce sustained change in society.

1.2 Research problem

South Africa is confronted with complex problems and challenges which includes sustainable development.

1.3 Research opportunity

Industrial engineering can solve complex problems and sustainable development issues using transdisciplinarity.

1.4 Research aim

The aim of this research is to develop an artefact that will facilitate transdisciplinary problem-solving and sustainable development in South Africa.

This research paper is structured with the literature review in section 2, methods presented in section 3 and the artefact design and presentation in section 4. Conclusions and recommendations constitute section 5.

2 LITERATURE REVIEW

2.1 Transdisciplinarity

Industrial engineering is argued to be multidisciplinary in nature. This deliberate configuration allows it to build on a vast array of knowledge domains to produce creative solutions to complex problems. Recently, academic scholars and practitioners have become more fixated on the notion of transdisciplinary knowledge and transdisciplinary solutions. To appreciate the evolution of transdisciplinary research, one must first contextualise its antecedents, namely disciplinary, multidisciplinary and interdisciplinary research. Research has also tried to define the differences between multi-, inter- and transdisciplinary sustainability research by a framework which found this often has blurred understanding [13]. According to Tress, et al. [14], disciplinarity is siloed between disciplines whereas multidisciplinary has loose cooperation between various disciplines during the knowledge exchange and theory development. In contrast, transdisciplinary type research has various goals that involve academic and non-academic knowledge bodies. This is best explained and imagined using Figure 1.

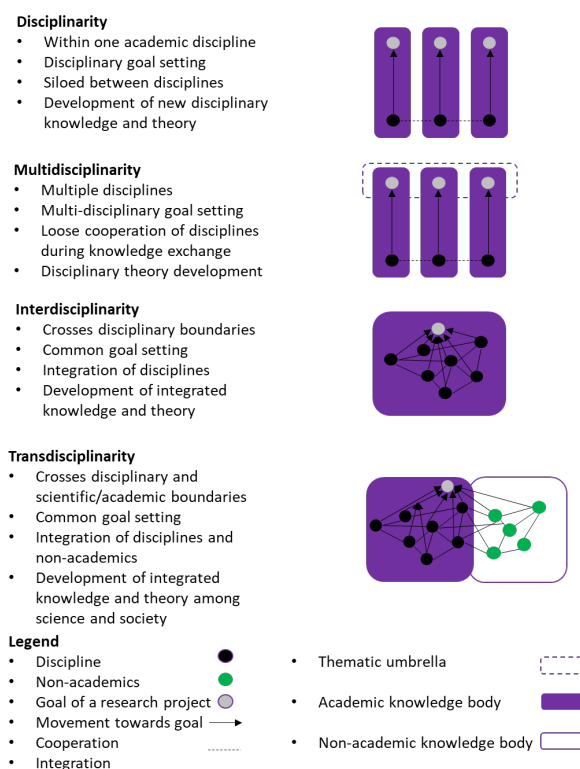


Figure 1: Transdisciplinary, interdisciplinary, multidisciplinary and disciplinary illustration redrawn from Tress, et al. [14]

Dalton, et al. [15] believe that in collaborative research that forms part of a multidisciplinary system, individual researchers provide concise but fragmentary solutions embedded within loosely designed and dynamic meta-problem superstructures. A year later, the same researchers explored interdisciplinary research. The researchers forge this as a system comprised of researchers assembled through false formation and morphing into a central organising principle that combines intention by unifying aims and methodologies [16].

For South African challenges, transdisciplinary approaches are the way forward. Dhansay, et al. [17] mention the Global Change Program highlighting the importance of transdisciplinary solutions to address the multifaceted issues in South Africa. In a transdisciplinary project, the venture undergoes three distinct stages, problem framing, problem analysis and exploring impact [18]. According to Pohl, et al. [19], a transdisciplinary project connects the realm of science, rigor and understanding with the realm of practice, relevance and design. This journey co-produces knowledge through learning and integration as a multidimensional interactive process involving many stakeholders. The gains from transdisciplinary research have maintained a positive impact on society which drives other forms of transdisciplinary research. Several transdisciplinary knowledge domains have emerged. One close to industrial engineering is that of industrial ecology. Industrial ecology strives to seek a balance between industrial metabolism (productivity gains) and ecological metabolism (preservation of nature) by viewing industrial and natural systems with interaction [20].

This research paper argues that Industrial engineering can perpetuate transdisciplinary knowledge due to its high multidisciplinary nature, industry relevance and systems thinking that gives a holistic perspective as masters of integration. This argument is also supported by Peruzzini, et al. [21], those who believe that Industrial Engineering is becoming increasingly viewed as a transdisciplinary field with particular reference to Industry 4.0. Sperotto [22] even recommends that academic institutions prescribe methods for the industrial engineering profession to lead rapid changes in the social and industrial environment for the needs of industry, the human-machine relationship and cultural aspects of society. It is therefore also befitting that transdisciplinary knowledge be explored since it considers academics and learned practitioners. There are however a myriad of challenges faced by transdisciplinary research, namely [23]:

- Diverse definitions and understandings of transdisciplinarity
- Complex and unclear relationships between methods, process phrases and knowledge types
- A gap exists between best practices and real-world projects
- Scarcity of high-level engagement
- Difficulty in evaluating the impact of the research

2.2 Future cones and strategic foresight

Society has long studied the effects of the past and imagining, preparing, and embracing what lies ahead. This fixation presents itself in various concepts concerning future thinking, future studies and predicting the future. Future studies can visualise the possibilities of many futures since it is most believed that the future is many. This visualisation is carefully crafted using future cones and the cone of possibilities.

The concept of future cones has been adapted, refined and improved upon over many years. An early, and widely accepted proposition is the version of the cone of uncertainty. Bauman [24] presents a cone that argues that as time progresses, the level of uncertainty diminishes as less likely outcomes and possible futures become non-probable. Since then, this idea has been contested and argued that time progression increases the likelihood of more futures. Research efforts by Gall, et al. [25] uncover and report on variations of the future cone. Their outcome is to consolidate the versions using the characteristics that have been composed over many years. This revised future cone is depicted in Figure 2.

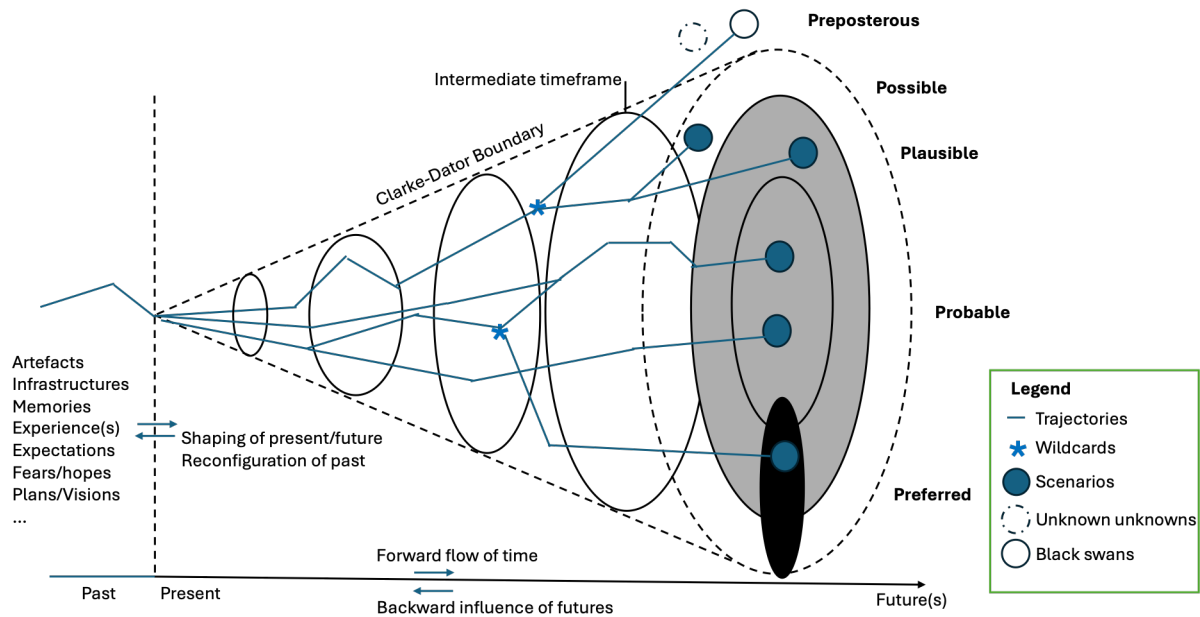


Figure 2: Revised future cone redrawn from Gall, et al. [25]

This revised model combines the concepts from 14 future cones using consistent characteristics. Each time element is subjected to a scenario that is dictated by the forward flow of time and the backward influence of futures with backcasting [26]. The model also accounts for linear temporality implying that time only flows in one direction. There also exists a widening range of possibilities with events creating distinctions between probabilities that yield new trajectories that can be multiple and non-linear in nature. The future also plays host to wildcards, which are deemed as high-impact, high-uncertainty events that can alter these trajectories [27]. Future cones form a crucial part of the foresight process.

Strategic foresight enables an enterprise to conceptualise strategies that allow entities to detect weak signals and wildcards by embracing environmental scanning methods and reflecting on strengths and internal capabilities [28]. One segment of any business is the technological advances that may follow. A technological foresight model by Güemes-Castorena, et al. [29] uses foresight to identify business opportunities using change drivers, Delphi, scenario planning and a technology roadmap. This combination demonstrates the application of foresight welcoming a diverse set of tools that can complement the endeavour an organisation or society pursues.

For the industrial engineer, the ability to apply foresight and future thinking would prove valuable to their diverse set of problem-solving skills. Not only will the prediction, planning and response to future outcomes make organisations more resilient, but this would also empower society to embrace more dynamic changes with more scenarios accounted for and understood. It also cultivates an environment eager for change. This could indirectly increase buy-in for the very creative solutions needed to solve the complex problems that dominate our world.

2.3 Sustainable Development Goals

For any country to make a meaningful impression on society and reap sustained value for the future, the sustainable development goals are pivotal. The 17 Sustainable development goals (SDGs) were introduced in 2015 as part of the UN 2030 Agenda for a sustainable society which accounts for social, environmental and economic pillars [30]. The 17 SDGs are [31]:

- SDG 1: No poverty
- SDG 2 - Zero hunger

- SDG 3 - Good health and wellbeing
- SDG 4 - Quality education
- SDG 5 - Gender equality
- SDG 6 - Clean water and sanitation
- SDG 7 - Affordable and clean energy
- SDG 8 - Decent work and economic growth
- SDG 9 - Industry, Innovation and infrastructure
- SDG 10 - Reduced inequalities
- SDG 11 - Sustainable cities and communities
- SDG 12 - Responsible consumption and production
- SDG 13 - Climate action
- SDG 14 - Life below water
- SDG 15 - Life on land
- SDG 16 - Peace, justice and strong institutions
- SDG 17 - Partnerships and goals

These are broad-reaching and address the shortcomings of the Millennium Development Goals (MDGs) [32, 33]. The SDGs form part of orientation knowledge which formulates and justifies the goals and objectives for a social change process [23]. These goals aspire to lead a transformational process which begins with incremental change, moving on to accelerated radical change (increasingly seen as inevitable) and finally leading to a system change as an end transformational state [34].

The SDGs lay the groundwork for sustainable transformations together with sustainable development. Voulvoulis, et al. [34] advise that systems thinking is needed for sustainability transformations. Fortuitously, the industrial engineering profession prides itself on its systems view and systems thinking approach which complement the execution of SDGs, and so it becomes the industrial engineer who can aid in the roll-out and strategic planning needed for the SDGs to take effect.

3 METHODOLOGY

The nature of this research is explorative since it takes on a constructivist paradigm. To achieve the aim of the research, a new methodology is proposed. This methodology is coined as the ACD methodology which can be used for high-level abstraction for theory development as part of problem-orientated research similar to Gregor, et al. [35]. The stages for this methodology are illustrated in Figure 3.

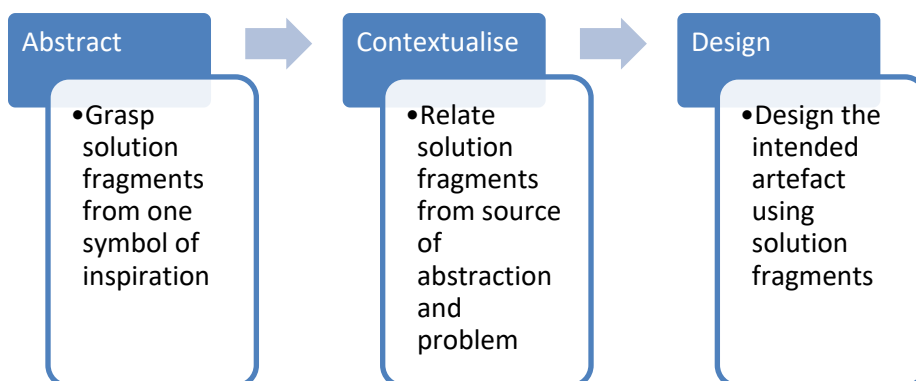


Figure 3: ACD methodology

During the first phase, the researcher identifies a symbol that either mimics or serves as a metaphor for the improvement initiative. As soon as this symbol, icon, artefact or analogy is obtained, the functions are exposed, critiqued and used to brainstorm solution fragments that will be used later on. The use of abstraction is able to simplify complex relationships that may exist, but also guide design decisions [36].

The Contextualise phase welcomes case specific circumstances, characteristics and methods of application in the same geographical region or subject matter orientated around the problem. Two aspects can be contextualised, the problem or the assortment of solution fragments.

In the Design phase, the fragments in the abstraction and contextualisation phase are pieced together to create the intended artefact. The solution fragments must become inherent subcomponents or features that belong to the symbol, icon or artefact identified in the abstraction phase.

In this research the data collection with aid in developing a literature-based lighthouse model that leverages Industrial Engineering knowledge. In the contextualise phase, the data will thus require pertinent literature on artefacts that can support sustainable development in South Africa. They will be summarised in table format so as to inform the design phase. These findings are now presented in section 4.

4 INDUSTRIAL ENGINEERING FORESIGHT MODEL

4.1 Lighthouse abstraction

This research takes inspiration from a lighthouse since it is a symbol of clarity, direction, and measurement as monitoring mechanisms. It gives strategists a sense of alignment as to where they currently are, where they are going and how far away, they are from the shore or their intended destination. A lighthouse simply illuminates the way forward.

This research is not the first to explore the concept of a lighthouse for design inspiration. Furthermore, it is also not the first to consider a lighthouse with regard to sustainability. The research by Holmberg and Larsson [37] produce an innovative sustainability lighthouse that guides sustainability transitions in socio-technical systems. This model is encapsulated in Figure 4.

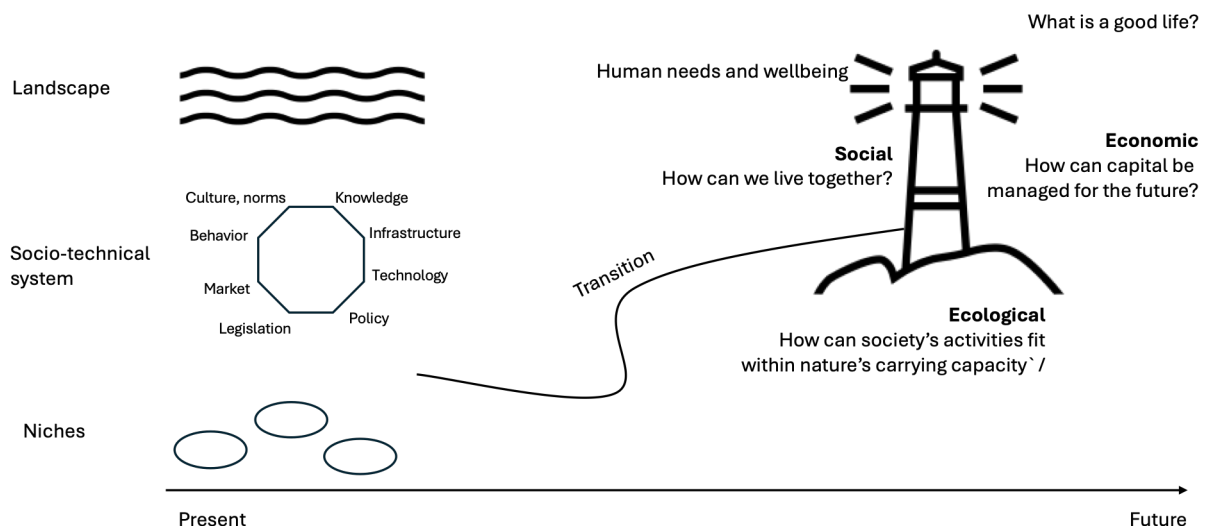


Figure 4: Sustainability lighthouse guiding socio-technical systems redrawn from Holmberg and Larsson [37]

This model guides sustainability by bridging the issue of sustainability transitions, forming part of a backcasting process and appeals to modes of transdisciplinary research and its relevant actors [37]. This also validates the selection of a lighthouse according to the purpose of this research seeing that this focuses on sustainable development, demonstrates foresight components and speaks to transdisciplinarity. This model highlights leadership processes that must consider social, economic and ecological aspects and eight core socio-technical system components.

In South Africa, research into socio-technical transitions is also presented in the literature. Asiimwe and De Kock [38] perform a bibliometric analysis on the interconnectedness and degree to which Industry 4.0 can be used in sustainability or socio-technical transitions. It was found that systems engineering, innovation, industrial production, technology adoption and digitalization are among many core components.

The clockwork and exact mechanisms that execute the function of a lighthouse are worth abstracting. The functionality is derived from the lens, turntable, base and clock mechanism that is supported by a weight. This is demonstrated in Figure 5.

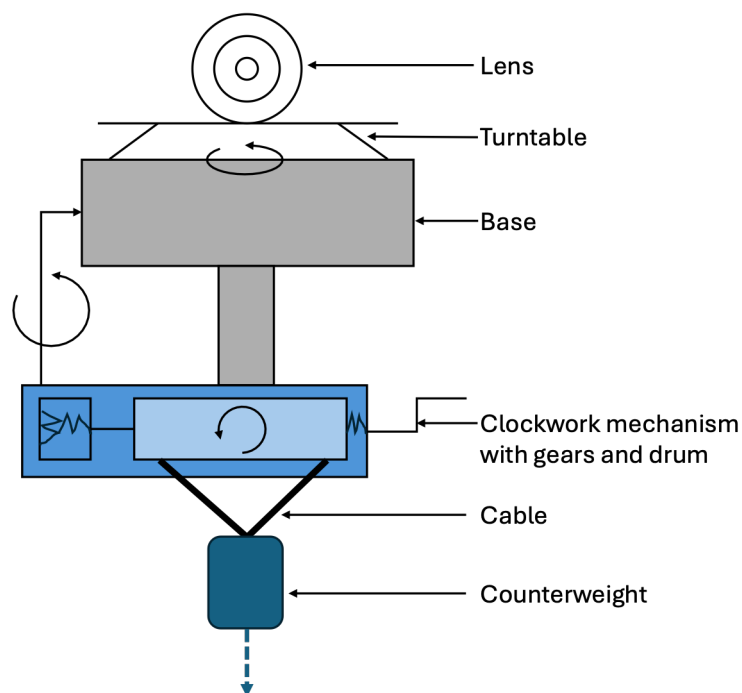


Figure 5: Lighthouse mechanisms redrawn from the Sheringham Point Lighthouse Preservation Society [21]

The visibility of the lighthouse is made possible by a 360-degree rotating turntable that ensures the light is visible in all directions. This alludes to any specific solution needing multiple perspectives. A counterweight drops a cable that rotates the clockwork drum mechanism to help drive the rotation throughout the entire light mechanism. This grounding symbolises relevance and being in tune with your surroundings. It now becomes more important that each idea or solution must have relevance or contextualisation, but also complement and appeal to the circumstances for the intended solution.

Every lighthouse in a specific region in the world has a unique signature. The composition of this signature uses a specific flash pattern which entails a colour of light shone with a certain light emission duration and spacing thereof [39]. The most prominent light colour across South African shorelines is white, hence hues of black and white will be used in the model.

4.2 Contextualisation

To contextualise the solution with the intent to be relevant and add value in South Africa, the research conducted in the country must be included. In order to succinctly present some of the relevant research in the field, Table 1 categorises artefacts predominantly developed in the South African Industrial Engineering domain that can be used for transdisciplinary problem-solving and sustainable development. The table provides the title of the research paper, the authors, the specific artefact, the rationale for its selection and the design consideration that will be used in the design and visualisation of the artefact for this research.

Table 1: Summary of Industrial Engineering work relevant to this research

Title	Authors	Artefact description and	Rationale for selection	Design consideration
The industrial engineering identity: From historic skills to modern values, duties and roles	Darwish and Van Dyk [40]	Industrial engineering identify tree model on the identity and role of IE	Focused on the industrial engineering discipline	Balance, industrial and systems thinking, design, engineering, management and proactiveness
An engineering approach to an integrated value proposition design framework	Alessandro, et al. [41]	A value proposition design framework that caters for new value proposition launches using Kano, Blue Ocean strategy and Generalised Bass model for a more customer-centric view	South Africa is a service economy and competitiveness is crucial for economic prosperity	Value creation must have functional, economic, psychological and creative value
A Lean implementation framework encompassing South African Ubuntu	Mangaroo-Pillay [42]	A South African Lean-Ubuntu analogy of the management principles	The framework prescribes execution across three execution levels in organisations	Collectivism should also take preference, considering problem-solving, processes, people and philosophy
Rapidly arriving futures: future readiness for Industry 4.0	Botha [43]	Industry 4.0 Readiness assessment using aspects from future thinking	Future thinking, scenario planning and wildcards used	Some form of impact assessment is important with future thinking
Towards a customized foresight model on “disaster risk management” in developing countries	Sayah Mofazali and Jahangiri [44]	Preparedness approaches and methods to disaster risk management are proposed	The findings relate to South Africa as a developing country	Preparedness features as the core aspect for risk management

Title	Authors	Artefact description and	Rationale for selection	Design consideration
Exploring the disconnect between bodies of literature pertaining to socio-technical transitions and technology assessment (Part 2): Linkage analysis	De Kock and Brent [45]	Insights on socio-technical and technology management literature revealed using a bibliometric and linkage analysis	Various keyword and theme occurrences relate to sustainable development	Innovation, economics, multi-level perspective and appropriate research methodologies are key occurrences
Learning to frame complex sustainability challenges in place: Explorations into a transdisciplinary “Challenge Lab” curriculum	McCrory, et al. [46]	A method for framing problems using four principles	Framing sustainability challenges in transdisciplinary is an initial stage in the problem-solving approach	Four principles for backcasting proposed as a slope
Towards a framework for systemic creativity in engineering organisations	Bam and Vlok [47]	Seven core elements for systemic creativity proposed	Creativity and systemic solutions resolve complex problems	Person, process, place, product, influence of leadership, persuasion and potential are seven elements for consideration

These solution fragments from the rightmost column of Table 1 are design considerations transferred into the design phase to address transdisciplinarity and sustainable development in South Africa.

4.3 Design logic and visualisation

Due to the medium to high level of abstraction required to embody Industrial Engineering traits that support transdisciplinary problem-solving and sustainable development, the design logic draws on the mechanisms of a lighthouse and the theory previously discussed. These are the attributes extracted from the solution fragments:

- Stakeholder engagement, co-creation, collaboration, problem analysis and impact assessment from transdisciplinarity
- Multiple perspectives, relevance, a strong foundation and black and white shades in the design from lighthouse abstraction
- Relevance, grounding in theory and contextualism from clockwork mechanism abstraction
- Backcasting was also deemed a suitable approach for realising the SDGs and African Union’s Agenda 2030 Goals [37].
- Backcasting, risk evaluation and scenario planning from future cones and foresight

- Technology management, collaboration and systemic change derived from the SDGs
- Systems thinking, design, engineering and management from Darwish and Van Dyk [40]
- Solution fragments related to the knowledge domains from Salvendy [1] that translate into operations management, engineering economics, human factors engineering, technology management and operations research as underlying industrial engineering knowledge domains for the lighthouse base
- Openness, people-centred processes, culture from Mangaroo-Pillay [42] adapted to people and culture
- Value creation from Alessandro, et al. [41]
- Innovation, economics, multi-level perspective and appropriate research methodologies from De Kock and Brent [45] used to create cascading levels in the lighthouse
- Culture, knowledge and technology from Holmberg and Larsson [37] are factored into the design
- Innovation and systems thinking from Asiimwe and De Kock [38] that ensure sustainable transitions
- Impact assessment from Botha [43]
- Four backcasting steps from McCrory, et al. [46] redirected as the slope from the lighthouse to the shore
- Seven elements for systemic creativity from Bam and Vlok [47] where process, leadership and potential are used in the lighthouse

All of the aforementioned solution fragments have been contextualised and morphed into a total of 28 solution fragments that are depicted in the lighthouse model in Figure 6.

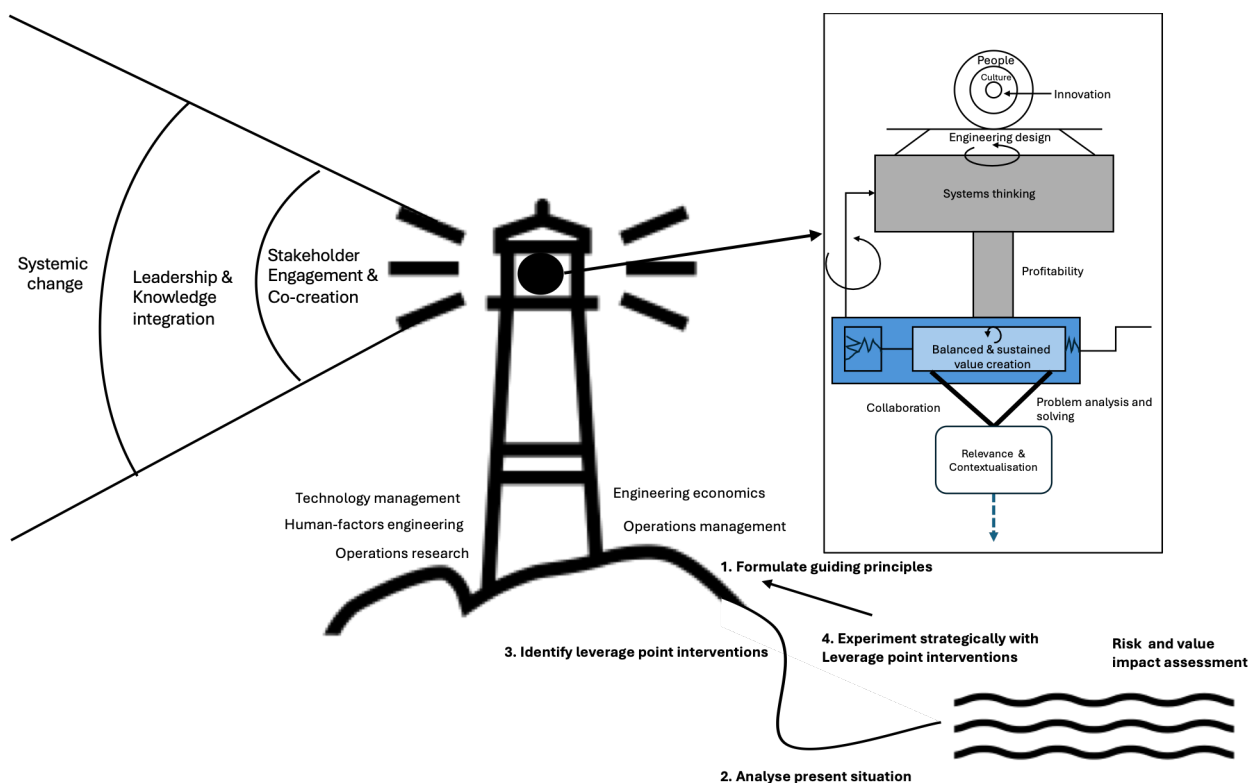


Figure 6: Industrial Engineering foresight model for transdisciplinary problem solving and sustainable development

4.4 Application and implications

The abstraction and subsequent visualisation coalesces this as a lighthouse model that harnesses and builds on the work from other South African Industrial Engineering artefacts. It demonstrates multiple perspectives using the skeleton 3D visualisation and five-sided theoretical base that represents the industrial engineering knowledge domains deemed most relevant to the research aim. The model walks towards the lighthouse through the backcasting process, builds up using the pertinent industrial engineering knowledge domains, leverages on the core clock and light mechanisms before projecting far-reaching attributes for its success.

Rittel and Webber [48] mention that for wicked problems, a range of possible solutions is the best resolve. Hence, this model should guide its user in producing a generic or case specific solution. The backcasting is applied at the bottom of the model, where the risk and value impact assessment lies in deep waters containing further complexities. The clockwork mechanisms embody the core aspects which were most recursive in the contextualisation stage of the research. The lens is comprised of people centredness and innovation at its core. Finally, the light begins with stages, ultimately leading to systemic change.

The model serves as a method to creating transdisciplinary solutions by providing the skeleton structure and crucial solution fragments that can foster systemic change through integrated knowledge and leadership that respects all stakeholders through co-creation. The implication of this model is that although holistic and generic, it demonstrates the valuable contribution industrial engineers can make when tackling complex solutions that exist in South Africa and other developing countries.

5 CONCLUSIONS AND RECOMENDATIONS

This research presents an industrial engineering foresight model for transdisciplinary problem-solving and sustainable development in South Africa. Not only does this strive to solve convoluted problems, but it also gives direction towards a problem-solving approach that the industrial engineer can lead irrespective of their industry.

Despite the advances this research makes, much like any research, there are of course shortcomings. One of the clear limitations is that this is unspecific to a sector or industry in South Africa. Therefore, this model can be repackaged to better suit set industries. Another drawback is that this has placed focus on South Africa, and while this could still easily apply to other developing countries, this is yet to be determined. Adaptations of this can look at modifications in other parts of the world.

Although this research is built on the icon or symbol of a lighthouse, alternative studies can explore other symbols for abstractions, but also, apply a lighthouse to contextualise and solve pressing issues.

The interest in the African Union's Agenda 2063 goals is gaining much traction in academia. These 19 goals envisage a means of boosting economic growth and development through transformation on the continent. Even though the SDG's have been factored into the design of the lighthouse model, to make this model more relevant to Africa, these goals could be considered and used for modifications.

Efforts can be made to have the findings from this research cascade further down the knowledge supply chain or into the quadruple helix. In this way, the components that belong to the lighthouse model may add more technical value to industry, academia, government and civil society.

A relevant and popular quote from the Harry Potter franchise belongs to Professor Albus Dumbledore. In this fantasy novel series by Rowling [49], he said :

"Happiness can be found, even in the darkest of times, if one only remembers to turn on the light."

This symbolises that the switch could resemble Industrial Engineering know-how, instincts, or traits that we embody. For us to "turn on the light" and find happiness in our solution, we must be vigilant of our impact on society in terms of sustainable development as we embark on new challenges, reach new horizons and sail in white water. As industrial engineers, we can solve the complex issues we face through collaboration, integrated knowledge, creative problem-solving, systems thinking and foresight.

6 REFERENCES

- [1] G. Salvendy, *Handbook of industrial engineering: technology and operations management*. John Wiley & Sons, 2001.
- [2] C. S. Schutte, D. Kennon, and W. Bam, "The status and challenges of industrial engineering in South Africa," *South African Journal of Industrial Engineering*, vol. 27, no. 1, pp. 1-19, 2016.
- [3] M. Mangaroo-Pillay and M. Roopa, "Beyond the industrial engineering frontier: A few steps in history and a giant leap into the future," *South African Journal of Industrial Engineering*, vol. 32, no. 3, pp. 1-9, 2021.
- [4] B. Smith, "Finding solutions to complex social problems in South Africa," 2012.
- [5] M. W. Legotlo, "Challenges and issues facing the education system in South Africa," 2014.
- [6] J. Kolko, "Chapter Seven - Wicked Problems," 2011.
- [7] V.-P. Niskanen, M. Rask, and H. Raisio, "Wicked problems in Africa: A systematic literature review," *Sage Open*, vol. 11, no. 3, p. 21582440211032163, 2021.
- [8] R. Biggs *et al.*, "Strategies for managing complex social-ecological systems in the face of uncertainty: examples from South Africa and beyond," *Ecology and Society*, vol. 20, no. 1, 2015.
- [9] G. W. Casey, "Leading in a 'VUCA' world," *Fortune*, vol. 169 5, pp. 75-6, 2014.
- [10] R. Dhillon and Q. C. Nguyen, "Strategies to respond to a VUCA world," 2021.
- [11] M. S. Haque, "The Fate of Sustainable Development Under Neo-Liberal Regimes in Developing Countries," *International Political Science Review*, vol. 20, pp. 197 - 218, 1999.
- [12] D. J. DeTombe, "Towards sustainable development: a complex process," *International Journal of Environment and Sustainable Development*, vol. 7, pp. 49-62, 2008.
- [13] P. Stock and R. J. Burton, "Defining terms for integrated (multi-inter-trans-disciplinary) sustainability research," *Sustainability*, vol. 3, no. 8, pp. 1090-1113, 2011.
- [14] G. Tress, B. Tress, and G. Fry, "Clarifying integrative research concepts in landscape ecology," *Landscape ecology*, vol. 20, pp. 479-493, 2005.
- [15] A. Dalton, K. Wolff, and B. Bekker, "Multidisciplinary Research as a Complex System," *International Journal of Qualitative Methods*, vol. 20, p. 16094069211038400, 2021, doi: 10.1177/16094069211038400.
- [16] A. Dalton, K. Wolff, and B. Bekker, "Interdisciplinary Research as a Complicated System," *International Journal of Qualitative Methods*, vol. 21, p. 16094069221100397, 2022, doi: 10.1177/16094069221100397.

- [17] T. Dhansay, A. Serper, B. Linol, S. Ndлуvo, I. Perumal, and M. Wit, "Transdisciplinarity within South Africa's global change research: How (well?) are we doing?," *South African Journal of Science*, vol. 111, pp. 1-4, 2015.
- [18] C. Pohl, J. T. Klein, S. Hoffmann, C. Mitchell, and D. Fam, "Conceptualising transdisciplinary integration as a multidimensional interactive process," *Environmental Science & Policy*, vol. 118, pp. 18-26, 2021.
- [19] C. Pohl, P. Krütli, and M. Stauffacher, "Ten reflective steps for rendering research societally relevant," *GAIA-Ecological Perspectives for Science and Society*, vol. 26, no. 1, pp. 43-51, 2017.
- [20] B. R. Allenby, "Industrial ecology and design for environment," *Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, pp. 2-8, 1999.
- [21] M. Peruzzini, N. Wognum, C. Bil, and J. Stjepandić, "Special issue on 'transdisciplinary approaches to digital manufacturing for industry 4.0'," *International Journal of Computer Integrated Manufacturing*, vol. 33, pp. 321 - 324, 2020.
- [22] F. Sperotto, "The development of the industrial engineering profession in South Africa (1)," *South African Journal of Industrial Engineering*, vol. 26, no. 2, pp. 1-9, 2015.
- [23] M. G. Lawrence, S. Williams, P. Nanz, and O. Renn, "Characteristics, potentials, and challenges of transdisciplinary research," *One Earth*, vol. 5, no. 1, pp. 44-61, 2022.
- [24] C. Bauman, "Accuracy Considerations for Capital Cost Estimation," *Industrial & Engineering Chemistry*, vol. 50, no. 4, pp. 55A-58A, 1958/04/01 1958, doi: 10.1021/i650580a748.
- [25] T. Gall, F. Vallet, and B. Yannou, "How to visualise futures studies concepts: Revision of the futures cone," *Futures*, vol. 143, p. 103024, 2022.
- [26] K. H. Dreborg, "Essence of backcasting," *Futures*, vol. 28, no. 9, pp. 813-828, 1996/11/01/ 1996, doi: [https://doi.org/10.1016/S0016-3287\(96\)00044-4](https://doi.org/10.1016/S0016-3287(96)00044-4).
- [27] M. Barber, S. Analyst, and B. Vic, "Wildcards-Signals from a future near you," *Journal of Futures Studies*, vol. 11, no. 1, pp. 75-94, 2006.
- [28] A. Derkachenko and A. Kononiuk, "The application of the Foresight Maturity Model (FMM) in a manufacturing company," 2021.
- [29] D. Güemes-Castorena, G. Romero Rivera, and A. Villarreal González, "Technological foresight model for the identification of business opportunities (TEFMIBO)," *Foresight*, vol. 15, no. 6, pp. 492-516, 2013.
- [30] T. Hák, S. Janoušková, B. Moldan, and A. L. Dahl, "Closing the sustainability gap: 30 years after "Our Common Future", society lacks meaningful stories and relevant indicators to make the right decisions and build public support," *Ecological Indicators*, vol. 87, pp. 193-195, 2018/04/01/ 2018, doi: <https://doi.org/10.1016/j.ecolind.2017.12.017>.
- [31] U. Nations, "Transforming our world: The 2030 agenda for sustainable development," *New York: United Nations, Department of Economic and Social Affairs*, vol. 1, p. 41, 2015.
- [32] S. Fukuda-Parr, "From the Millennium Development Goals to the Sustainable Development Goals: shifts in purpose, concept, and politics of global goal setting for development," *Gender & Development*, vol. 24, no. 1, pp. 43-52, 2016.

- [33] M. Roopa, "Business Engineering 4.0: The Transformation of a University Course in Response to Industry 4.0, Sustainable Development Goals, & Covid-19 in South Africa," *International Journal of Engineering Pedagogy*, vol. 13, no. 8, 2023.
- [34] N. Voulvoulis *et al.*, "Systems thinking as a paradigm shift for sustainability transformation," *Global Environmental Change*, vol. 75, p. 102544, 2022.
- [35] S. D. Gregor, O. Müller, and S. Seidel, "Reflection, Abstraction And Theorizing In Design And Development Research," in *European Conference on Information Systems*, 2013.
- [36] S. P. Hoover, J. R. Rinderle, and S. Finger, "Models and abstractions in design," *Design Studies*, vol. 12, pp. 237-245, 1991.
- [37] J. Holmberg and J. Larsson, "A sustainability lighthouse—Supporting transition leadership and conversations on desirable futures," *Sustainability*, vol. 10, no. 11, p. 3842, 2018.
- [38] M. M. Asimwe and I. H. De Kock, "An analysis of the extent to which industry 4.0 has been considered in sustainability or socio-technical transitions," *South African Journal of Industrial Engineering*, vol. 30, no. 3, pp. 41-51, 2019.
- [39] S. P. L. P. Society. "How the lighthouse works." <https://sheringhamlighthouse.ca/the-lighthouse-2/how-the-lighthouse-works/> (accessed May 2024).
- [40] H. Darwish and L. Van Dyk, "The industrial engineering identity: from historic skills to modern values, duties, and roles," *South African Journal of Industrial Engineering*, vol. 27, no. 3, pp. 50-63, 2016.
- [41] B. Alessandro, C. Caterina, L. Marinella, R. Francesco, and Z. Alessandro, "Biomimicry thinking: methodological improvements and practical implementation," *Bioinspired, Biomimetic and Nanobiomaterials*, vol. 6, no. 2, pp. 87-101, 2017, doi: 10.1680/jbibn.16.00007.
- [42] M. Mangaroo-Pillay, "A Lean implementation framework encompassing South African Ubuntu," North-West University (South Africa). 2022.
- [43] A. P. Botha, "Rapidly arriving futures: future readiness for Industry 4.0," *South African journal of industrial engineering*, vol. 29, no. 3, pp. 148-160, 2018.
- [44] A. Sayah Mofazali and K. Jahangiri, "Towards a customized foresight model on “disaster risk management” in developing countries," *Foresight*, vol. 20, no. 5, pp. 467-487, 2018.
- [45] I. H. De Kock and A. C. Brent, "Exploring the disconnect between the bodies of literature pertaining to socio-technical transitions and technology management (part 2): a linkage analysis," *South African Journal of Industrial Engineering*, vol. 33, no. 1, pp. 65-86, 2022.
- [46] G. McCrory, J. Holmén, J. Holmberg, and T. Adawi, "Learning to frame complex sustainability challenges in place: Explorations into a transdisciplinary “challenge Lab” curriculum," *Frontiers in Sustainability*, vol. 2, p. 714193, 2021.
- [47] L. Bam and P. Vlok, "Towards a framework for systemic creativity in engineering organisations," *South African Journal of Industrial Engineering*, vol. 27, no. 2, pp. 95-108, 2016.
- [48] H. W. Rittel and M. M. Webber, "Dilemmas in a general theory of planning," *Policy sciences*, vol. 4, no. 2, pp. 155-169, 1973.
- [49] J. K. Rowling, *Harry Potter and the Prisoner of Azkaban*. Bloomsbury Children's Books, 2013.

Chapter 7

7 A transdisciplinary pyramid waterfall fountain model for a sustainable competitive advantage

This chapter serves as a research manuscript **resubmitted** to the Journal of **Cleaner Production** (Q1) after double blind review.

Abstract: Organisations in developing countries face mounting pressure to pursue environmental sustainability while remaining competitive, yet the knowledge required to do so is fragmented across the disciplines of Industrial Engineering (IE) and Environmental Sustainability (ES). This study develops a transdisciplinary (TD) framework that integrates IE and ES knowledge to support a sustainable competitive advantage (SCA) in developing-country contexts. The Abstract, Contextualise and Design (ACD) methodology was adapted for this purpose. Qualitative data, comprising publications from a prior systematic literature review and 24 practitioner interviews conducted in South Africa, were analysed using systematic text condensation, quantitised, and filtered through a newly proposed Pareto-Weighted Thematic Analysis (PWTA). Alluvial and sunburst diagrams were then used to trace how strategies, theories, methods and practices combine into application streams across the strategic, tactical and operational levels of business execution. The resulting artefact, a pyramid waterfall framework, organises the retained knowledge components on four configured sides, along which knowledge cascades from strategy to practice and facilitates organisational learning. This research demonstrates how organisations in developing countries can integrate IE and ES knowledge in pursuit of a sustainable competitive advantage.

Keywords: Sustainable Competitive Advantage, Industrial Engineering, Environmental Sustainability, Transdisciplinary knowledge, Developing countries

Status: Resubmitted to the Journal of Cleaner Production on 13 August March after double blind review. Results and analysis are featured in Appendix C (knowledge components) and Appendix D (Pareto Analysis applied).

Introduction: Chapter 7 is the integrative and most substantial research output, submitted to the Journal of Cleaner Production, and it functions as the point at which the separate strands developed in Chapters 4, 5 and 6 are formally fused into a single transdisciplinary artefact. The chapter opens by locating itself at the intersection of innovation, sustainable competitive advantage (SCA), industrial engineering and environmental sustainability, restating that IE and ES remain loosely connected knowledge domains despite the clear opportunity for integration. It surveys the innovation literature to establish that failing to innovate risks losing competitive advantage altogether, and that sustainability-oriented innovation is increasingly treated as a strategic necessity rather than an optional extra, which is evidenced by rising governmental and international reporting pressure. The introduction is notably more extensively theorised than earlier empirical chapters, reviewing the three established sustainability pillars, the distinction between reactive and proactive environmental strategies, and the particular difficulty developing countries face in coordinating the skills and knowledge needed to pursue an SCA.

The chapter is explicit about its own novelty relative to its predecessors: it acknowledges that IE's affinity with ES has already been established (citing Chapters 4 and 5 directly), but argues that fragmented literature and the absence of a structured, integrative approach still leave organisations without clear guidance on how to convert that affinity into an actual sustainable competitive advantage. This absence of structured guidance, rather than a lack of raw knowledge, is identified as the chapter's specific contribution and point of departure.

Relevant research component: The research problem is paraphrased as fragmented research exists between IE and ES, with no clear guidance on how to ensure a sustainable competitive advantage for developing countries. The research aim is to develop a transdisciplinary framework that integrates IE and ES knowledge to ensure a sustainable competitive advantage for developing countries. A single central research question is posed, RQ1: "How can IE and ES knowledge be integrated into a TD framework for a sustainable competitive advantage in developing countries?" This is supported by two objectives, namely (1) to integrate IE and ES knowledge within TD contexts for developing countries, and to (2) design a TD framework using that integrated knowledge to ensure an SCA for developing countries. The chapter draws a careful conceptual distinction between a "model" (the operation or mechanism of an entity) and a "framework" (a more general plan for implementing theory). It also explicitly commits to producing a framework rather than a model, since the intended artefact is meant to be adoptable across multiple industries rather than describing a single fixed mechanism.

Methodology: Chapter 7 adapts the ACD (Abstract-Contextualise-Design) methodology first introduced in Chapter 6, explicitly citing and building on it, while introducing a substantial methodological innovation of its own, the Pareto-Weighted Thematic Analysis (PWTA). The chapter's raw data consists of two qualitative sources already generated elsewhere in the thesis: the 23 papers and their coded findings from the systematic literature review, and the 24 interview transcripts and their coded findings from Chapter

5. These two sources are combined using structured text condensation as a technique for cross-case analysis. The PWTA itself, inspired by preceding work on thematic analysis and the Pareto principle, proceeds by extracting code densities per theme, ranking themes from highest to lowest density, calculating cumulative weighted percentages, and then applying a threshold to isolate the "vital few" themes from the "trivial many,". In doing so, it explicitly operationalises the 80/20 rule to make an otherwise unwieldy qualitative dataset tractable for design purposes.

Within the ACD structure, the Abstraction phase draws its symbolic inspiration from water. The Contextualisation phase applies the PWTA to merge, deduplicate and reduce the combined dataset, aided by a morphological (Zwicky) box representation and the systems-thinking maturity model. Together, these justify treating the framework as an interpretive system capable of handling complex, high-uncertainty problems. Reliability and validity are addressed by noting that the SLR data already adhered to PRISMA and the interview data to Creswell and Creswell's protocol, giving the combined PWTA a defensible evidentiary base drawn from two independently validated qualitative studies.

Core findings: The PWTA data-consolidation process entails an initial pool of 234 knowledge components (drawn from Chapters 4 and 5 combined) that was reduced through deduplication and concept-merging to 197, then further reduced through Pareto-weighting to a final set of 107 vital few knowledge components, with thirteen SLR-derived components discarded at an earlier stage for not conforming to any IISE Body of Knowledge area. These surviving components were visualised through alluvial diagrams, showing top-down strategy-to-theory-to-practice flow, with efficiency, circular economy and sharing principles, environmental management, and the SDGs emerging as the highest cumulative-density strategies, as well as complementary sunburst diagrams which demonstrate the same relationships from a bottom-up, practice-to-strategy perspective.

These consolidated components were ultimately assembled into the central TD artefact, a four-sided pyramid structure with a shared knowledge core representing IE, ES and SCA. Each of the four sides carries six strategies, eight theories, and eight methods-and-practices, organised into distinct thematic clusters, side 1 emphasising efficiency and business performance, side 2 emphasising systems thinking and supply chain considerations, side 3 emphasising quantitative and life-cycle analysis techniques, and side 4 emphasising carbon neutrality and continuous improvement, with the whole structure designed to be navigated top-down (strategy to theory to methods and practice) in a manner that metaphorically mimics cascading water. The discussion situates this artefact within an existing SCA taxonomy, noting explicitly that it aligns with four of that taxonomy's six defined clusters (leaving leadership, shared value, market orientation and resource capabilities as areas not yet addressed), and argues that the PWTA methodology itself represents a transferable contribution, since it demonstrates that qualitative sustainability research can be rendered decision-oriented rather than purely descriptive.

Reflections: Chapter 7 is, by design, the thesis's synthesis chapter, and its central achievement is methodological economy. To explain further, rather than collecting a third independent dataset, it demonstrates real analytical ingenuity in re-using and re-weighting the two datasets already produced in Chapters 4 and 5, via the novel PWTA technique. This produces a genuinely new artefact rather than a mere restatement of earlier findings. This is a defensible and efficient research design choice, though it does mean the pyramid fountain model's evidentiary base, while doubly-grounded, is not independently validated against a third, fresh data source, a limitation the chapter itself explicitly and directly acknowledges when it notes that the artefact "has yet to be validated in real-world contexts, as co-implementation did not feature."

The conclusion is unusually forthright about the scope of what remains undone, calling out the absence of leadership, shared value, market orientation and resource capabilities from the finished artefact, the lack of any quantitative or simulation-based testing of the framework's internal structure, and the open question of how TD artefacts of this kind should even be validated, given that Scholz and Steiner's cited work argues TD validation is inherently more difficult than validating single-discipline research. These are not minor caveats; they collectively define the precise research agenda that the remaining chapters of the thesis, particularly Chapter 9's use case analysis and Chapter 10's confirmatory focus group, exist to address.

Inter-relationships across other chapters: Chapter 7 draws direct, explicit input from the SLR findings from Chapter 4, interviews documented in Chapter 5, and the extension of the ACD methodology first piloted in Chapter 6, whose figure is directly reproduced and cited within this chapter. In this sense, Chapter 7 does not simply follow Chapters 4 through 6 sequentially; it structurally absorbs their outputs, making it the point at which the separate empirical and conceptual strands become a single, unified artefact for the first time. This positioning also makes Chapter 7 the natural point of departure for everything that follows. The TD artefact produced serves as part of the multi-use case analysis (Chapter 9), but is also embedded here. This sets out to test real-world conformance by explicitly mapping published case studies against each side of the artefact. This is the same TD artefact subject to the CFG (Chapter 10) and discussions (Chapter 11) to validate and interrogate.

A transdisciplinary pyramid waterfall framework for a sustainable competitive advantage in developing countries

Abstract

Organisations in developing countries face mounting pressure to pursue environmental sustainability while remaining competitive, yet the knowledge required to do so is fragmented across the disciplines of Industrial Engineering (IE) and Environmental Sustainability (ES). This study develops a transdisciplinary (TD) framework that integrates IE and ES knowledge to support a sustainable competitive advantage (SCA) in developing-country contexts. The Abstract, Contextualise and Design (ACD) methodology was adapted for this purpose. Qualitative data, comprising publications from a prior systematic literature review and 24 practitioner interviews conducted in South Africa, were analysed using systematic text condensation, quantitised, and filtered through a newly proposed Pareto-Weighted Thematic Analysis (PWTA). Alluvial and sunburst diagrams were then used to trace how strategies, theories, methods and practices combine into application streams across the strategic, tactical and operational levels of business execution. The resulting artefact, a pyramid waterfall framework, organises the retained knowledge components on four configured sides, along which knowledge cascades from strategy to practice and facilitates organisational learning. The framework offers a structured, although not yet field-validated, means by which organisations in developing countries can integrate IE and ES knowledge in pursuit of a sustainable competitive advantage.

Keywords: Sustainable Competitive Advantage, Industrial Engineering, Environmental Sustainability, Transdisciplinary knowledge, Developing countries

1. Introduction

1.1 Context

This research landscape is positioned at the under-explored intersection of innovation, sustainable competitive advantages, industrial engineering and environmental sustainability for transdisciplinary knowledge creation within developing countries. It posits that the realms of industrial engineering and environmental sustainability are loosely connected solution spaces with opportunities to integrate their know-how to enable organisations to continue to innovate beyond the status quo.

Amidst continuous innovations, organisations are forced to remain resilient and adaptive to emergent technologies. Innovation continues to redefine processes or ways of thinking that challenge the status quo. The notions of innovation have created the need for organisations to become more effective, efficient and conservative in their use of

resources while simultaneously remaining competitive in their own market (Markley & Davis, 2007).

There has been considerable debate regarding innovation and its nature. Van de Ven (1986) defines innovation as the continuous development and implementation of new ideas within institutions over time. Without innovating, companies will be left behind (Siriram, 2011). Furthermore, failing to innovate can result in losing or not obtaining a sustained competitive advantage (Pisano, 2015). The innovation process itself contains a myriad of complexities ranging from ongoing innovation, unfolding within firms, networks, and communities, with evolutionary, relational, temporal and cultural sophistication discussed by Garud *et al.* (2013). Kahn (2018) details at least six forms of innovation that make the implementation more daunting for organisations. Due to the complexity in effectively innovating within any organisation, it has become elusive and often leads to incorrect decision-making (Gutierrez *et al.*, 2008; Kuratko *et al.*, 2014). The challenge is elevated even more when pursuing a sustainability agenda.

The interest in and prioritisation of sustainability agendas are ever-increasing and more consciously concerned with measuring and reporting (Al-Shaer *et al.*, 2022; Osobajo *et al.*, 2022). Not only do increased governmental legislation pressures and international initiatives create the need for this shift in strategic focus, but more so for organisational intent (Fatima *et al.*, 2023). In this way, a vast majority of researchers firmly believe strategy becomes the cornerstone for any organisation to embody profitable innovation (Cozzarin & Percival, 2006; Skjølsvik, 2020; Stewart & Fenn, 2006). Wang *et al.* (2022) demonstrate that environmentally focused innovation increases green competitiveness with knowledge sharing and organisational learning as enabling factors. In regard to product performance, proactive environmental strategies outdo reactive strategies (Chan *et al.*, 2022; Genç & Benedetto, 2019).

One of the challenges faced by any organisation is to be sustainable and sustain current practices (Jenkins, 2002; Perrott, 2014). The three established sustainability pillars include society, economy and the environment (Barton & Gutiérrez-Antinopai, 2020). This emphasises the need to measure sustainability performance (Finch, 2005). As a means to communicate this, organisations turn to various sustainability reporting frameworks and factors which have been tailored to the higher education, financial, and manufacturing sectors (Javed *et al.*, 2025; Li *et al.*, 2025; Rotondo *et al.*, 2025). Although all sustainability dimensions are crucial, environmental sustainability (ES) tends to receive the least focus in informal economies, as voiced by Eijdenberg *et al.* (2019).

Organisational sustainability, sustainable competitive advantages and corporate social governance are examples of strategic focus methods and topics used to meet sustainability objectives. A sustainable competitive advantage (SCA) involves a core strategic focus which contains environmental consideration while retaining or developing a competitive advantage in the market (Sharma & Gupta, 2024; Srivastava *et al.*, 2013). The nature of ES challenges is persistent and complex, warranting the need to employ an SCA. However, for developing countries, the coordination of appropriate activities is more challenging for skill and knowledge cultivation (Sharkie, 2003).

The body of empirical and conceptual work examining the intersection of sustainability and competitive positioning reveals a substantial, yet methodologically mixed, evidence base. A critical synthesis of the literature indicates that proactive environmental and social practices do not compromise financial performance. Early empirical validation provided by Gupta and Benson (2011) through an evaluation of the Innovest Global 100 demonstrated that sustainable firms maintain financial parity with conventional peers while securing strong competitive standing within their respective sectors. Further to this, Rattalino (2019) highlighted the operational mechanisms driving this relationship, documenting through a case study demonstrating how sustainability-driven innovation functions as a direct catalyst for a sustainable competitive advantage.

Despite these empirical insights, a significant portion of the current literature remains predominantly conceptual. Frameworks such as the one developed by Sapsanguanboon *et al.* (2025) conceptualise sustainable competitive advantage as an outcome driven primarily by executive leadership, continuous innovation, and systemic stakeholder collaboration. Similarly, through a systematic review of 143 sources, Bari *et al.* (2022) proposed that the development of sustainable dynamic capabilities is essential for firms seeking to reconfigure internal resources to achieve long-term market advantage.

However, translating these conceptual models into practice presents persistent organisational hurdles. As Githui and Njuru (2026) observed, while ESG adoption is recognised for its competitive benefits, widespread execution is frequently constrained by entrenched institutional barriers and pervasive short-term financial pressures. Consequently, while scholarly consensus firmly links sustainable strategies to enhanced competitiveness, closing the gap between conceptual capability frameworks and operational implementation remains an ongoing challenge within the field.

The engineering discipline is believed to hold potential in developing technologies and methods which transform sustainability principles (Biswas & John, 2022; Rahimifard & Clegg, 2008). One of the prevalent forms of engineering that combines business understanding, technology management and sustainability is Industrial Engineering (IE) (Bilge, 2017). Industrial Engineering is a discipline concerned with creating balanced value by innovatively designing solutions that rely on complex mathematics, management and social sciences, calling for the integration between people, processes, technology and systems (Darwish & Van Dyk, 2016; Mangaroo-Pillay & Roopa, 2021; Salvendy, 2001).

A highly recognised form of research which binds systemic problem-solving for environmental challenges is transdisciplinary (TD) research. TD is seen as a systemic, far-reaching research approach used to collaboratively problem-solve using a network of research skills and knowledge between various stakeholders (Bracken *et al.*, 2015). Furthermore, this form of research also complements the intent of IE. There is little debate that TD research is needed to solve complex and persistent problems in our interconnected and volatile world (Dalton *et al.*, 2021; Hadorn *et al.*, 2008; Jørgensen, 2016). It is also widely believed that TD research is well-suited to address ES challenges and climate change, as it requires strong collaboration and higher-order problem-solving at a systemic level (Apgar *et al.*, 2009; Klein, 2001).

The IE profession prides itself on its ability to creatively problem-solve using a vast array of knowledge within a multidisciplinary domain (Jovanovic, 2013; Salvendy, 2001). It therefore stands to reason that the IE discipline offers a diverse capability to reach beyond multidisciplinary domains and into the TD problem-solving domain. Its affinity to ES has been established, but it still does not effectively spur on and support ES imperatives (Roopa *et al.*, 2024; Tsoku *et al.*, 2024).

A unique challenge is the fragmented literature between IE and ES, which inadequately supporting an SCA for developing countries. This fragmentation leaves organisations with uncertainty when trying to integrate knowledge between IE and ES. With no structured approach, organisations will continue to have failed sustainability-oriented improvement initiatives (Brough *et al.*, 2020), depleted funds and lost competitiveness (Parnaby, 2014). This deficiency in understanding and structured guidance serves as the scope and contribution of this research.

The contribution of this study should be read against recent work at this intersection. Reviews of sustainability innovation and firm competitiveness confirm a predominantly positive but contingent relationship, while offering little guidance on how disparate bodies of engineering and sustainability knowledge should be combined in practice (Hermundsdottir & Aspelund, 2021). Strategic sustainability frameworks similarly integrate adjacent concepts such as the green, circular and bio-economy at the macro level, but do not translate this integration into discipline-level guidance for organisations (D'amato & Korhonen, 2021). What remains unaddressed, and what this study targets, is a structured, transdisciplinary mechanism for combining IE and ES knowledge levels geared towards strategies, theories, methods and practices for organisations in developing countries.

1.2 Research problem

The research problem identified in this study is that fragmented research exists between IE and ES, with no clear guidance on how to ensure a sustainable competitive advantage for developing countries.

1.3 Research aim

The aim is to develop a TD framework that integrates IE and ES knowledge to support a sustainable competitive advantage for developing countries

1.4 Research questions

To achieve the aim, the following research question has been postulated:

- RQ1: How can IE and ES knowledge be integrated into a TD framework for a sustainable competitive advantage in developing countries?

1.5 Research objectives

The following research objectives have been articulated to support the problem statement, aim and research questions:

- Objective 1: Integrate IE and ES Knowledge within TD contexts for developing countries.
- Objective 2: Design a TD framework using the integrated knowledge to support a sustainable competitive advantage for developing countries.

The terms model and framework cannot be used synonymously. Mangaroo-Pillay et al. (2022) differentiate between these two mental artefacts. A model is the operation or mechanism of an entity, whereas a framework is a more general plan for implementing theory. This research seeks to create an adoption framework linked to various industries, and so a framework will be the intended TD artefact. The structure of this paper presents pertinent literature on ES, SCA, TD, IE, and the sustainability narrative for developing countries in Section 2. The research methodology is presented in Section 3, followed by the TD framework, results and findings in Section 4. Discussions and implications are drawn in Section 5 before closing with conclusions and recommendations in Section 6.

2. Literature Review

2.1 Environmental sustainability

There has been more than a decade of debate on the definition and relevance of sustainability within the academic world (Toman, 1992). The notion of sustainability is geared towards meeting existing needs without undermining future capabilities (Emas, 2015). However, the way in which we perceive sustainability is already a complex relationship, as evidenced by the work of Lozano (2008) who explored different forms of visualising sustainability. Most illustrations follow the traditional 2-D representation with the Siloed, Mickey Mouse, Bullseye and Barstool sustainability models associated with the economy, environment and society through increased understanding (Darwish, 2018).

Environmental sustainability is understood as the preservation of human interaction with ecological systems (Morelli, 2011). For organisations, their perception and stance on environmental sustainability is case-specific and transcends across maturity levels (Sari *et al.*, 2021). These can share a benign, conflicting, synergetic or symbiotic relationship between operational gain and environmental performance in a similar fashion to the lean and green narrative defined by Zokaei *et al.* (2013). Although sustainability narratives have a pivotal influence on organisational strategy in organisations (Goodland *et al.*, 1993), they are not seen as a priority due to their high capital investment and trade-off when considering the interests of economic and political systems (Redclift, 2002). Some turn to nature capital since it contains value added for society, derived from nature (Willis & Petrokofsky, 2017). However, this is severely limited amidst growing pressures to abide by environmental legislation. Strategies rooted in sustainability are often used to remain competitive and relevant in volatile markets.

The emergence of circular economy (CE) principles has fundamentally reframed environmental sustainability discourse, extending beyond traditional linear consumption models. MacArthur (2013) defines the circular economy as a systems-level approach to economic development designed to benefit businesses, society, and the environment through the elimination of waste and the continual use of resources. CE models represent a paradigm shift that organisations are increasingly adopting to simultaneously reduce environmental impact and create economic value through resource efficiency, product redesign, and industrial symbiosis (Geissdoerfer et al., 2017; Kirchherr et al., 2017). This CE perspective offers organisations a strategic pathway to harmonise environmental stewardship with competitive advantage, particularly as regulatory frameworks increasingly mandate circular practices and consumer demand for sustainable products strengthens.

2.2 Sustainable Competitive Advantage

Sharma and Gupta (2024) summarise that a sustainable competitive advantage (SCA) represents the strides made by organisations to surpass competitors using environmental sustainability as part of their core strategic approach (Tiwari et al., 2020; Waqas et al., 2021). This need not be confused with the alternative explanation, which argues that a competitive approach can be followed that is developed, executed and managed to ensure sustainable differentiation and advantage over competitors, independent of environmental prosperity (Rodriguez et al., 2002). In this research, the former definition of a sustainable competitive advantage (SCA) will be used since this speaks to the fragmented literature that can promote an SCA when integrated. The inclusion of sustainability boosts customer loyalty while carefully navigating the challenge of greenwashing.

One taxonomy for SCA, designed by Sołoducho-Pelc and Sulich (2020) is configured around six core factors which explore aspects concerning innovation, market orientation, resource capabilities, people, environmental change, strategy and knowledge. These considerations support the case for a resilient, sustainable and differentiating strategy which organisations can formulate to outperform their competitors or make them irrelevant. These embrace environmental considerations which require ordered problem solving with integrated management and creative approaches (Game et al., 2014). It stands to reason that SCA can serve as one such approach to ensure competitiveness and ES through correct practices (Oduro & Haylemariam, 2025). To formulate artefacts that are integrated and creative, TD can be employed to solve the very complex and systemic nature of sustainability challenges.

Digital transformation has emerged as a critical enabler of sustainable competitive advantage in contemporary business environments. Bican and Brem (2020) argue that digital innovation and Industry 4.0 technologies create new opportunities for organisations to operationalise sustainability through enhanced transparency, optimised resource allocation, and real-time environmental performance monitoring. This technological dimension of SCA is particularly salient for organisations seeking to build resilient supply chains and demonstrate environmental accountability to increasingly conscious stakeholders.

2.3 Transdisciplinary research

TD is defined as a multi-faceted problem-solving strategy which involves a vast array of stakeholders housed within academia or industry through collaboration, which involves various stages concerning planning, design, production, implementation or dissemination (Wibeck *et al.*, 2022). TD research is also acknowledged for its work in sustainability solutions since it can address the wicked nature of sustainability challenges (Lang *et al.*, 2012).

According to Axelsson (2010), TD can integrate knowledge to solve sustainability issues with interdisciplinary approaches. Roopa *et al.* (2024) argue that Industrial Engineering (IE) is a discipline which can be used to create transdisciplinary knowledge under the caveat that stakeholders are involved in the knowledge creation and more so during its validation. This reaffirms that the TD solution can harness existing IE notions to creatively problem-solve.

Stakeholder engagement and co-creation are fundamental components of effective transdisciplinary research, distinguishing TD from conventional multidisciplinary approaches. Brouwer *et al.* (2019) emphasise that TD research requires deliberative engagement of diverse knowledge holders, including practitioners, policymakers, and affected communities. This interaction occurs throughout the research process to ensure solutions are both scientifically rigorous and contextually relevant. Furthermore, van der Hel (2016) demonstrates that TD research programmes that actively involve stakeholders in problem framing, solution development, and validation are significantly more likely to produce actionable outcomes and foster institutional change. This collaborative dimension is particularly critical for addressing sustainability challenges, which are inherently complex, multifaceted, and dependent upon the integration of scientific, practical, and local knowledge systems.

The intersection of sustainability, industrial development, and transdisciplinary problem-solving in developing country contexts requires approaches that leverage indigenous knowledge systems, local capabilities, and social entrepreneurship. Mensah (2019) argues that sustainable development in developing economies must balance environmental protection with poverty alleviation, economic growth, and social inclusion. These are dimensions often treated as competing priorities in developed country contexts. Furthermore, Pimm *et al.* (2015) demonstrate that developing countries possess significant opportunities to leapfrog traditional industrial pathways by adopting sustainable technologies and circular economy models, particularly when supported by appropriate policy frameworks, technology transfer mechanisms, and capacity-building initiatives. To contribute further to the discussion, Hart and Christensen (2002) emphasise that frugal innovation and resource-constrained problem-solving inherent to developing economies can yield transformative solutions applicable globally, provided these innovations are systematically integrated into transdisciplinary frameworks that amplify their scalability and impact.

2.4 Industrial Engineering

IE has been mirrored and spurred on by the four Industrial Revolutions (Mangaroo-Pillay & Roopa, 2021). This multidisciplinary field is notoriously known for its ability to improve systems, processes, products and services by intuitively and creatively designing integrated solutions which call on a vast array of knowledge areas to create balanced value (Darwish & Van Dyk, 2016; Salvendy, 2001).

Although work of Tsoku *et al.* (2024) has explored the relevance of IE with sustainability, the profession is argued to have inculcated notions of high material consumption at the cost of increased productivity (Darwish, 2018). This is further problematised by the absence of sustainability considerations within the Bodies of Knowledge formulated by the Institute of Industrial and Systems Engineers, and the knowledge domains from the Handbook of Industrial Engineering (IISE, 2021; Salvendy, 2001). This oversight demonstrates that the IE profession is yet to meaningfully contribute to or receive formalised recognition for its sustainability problem-solving capabilities.

Contemporary scholarship increasingly recognises IE's potential to facilitate sustainable innovation through systems thinking and lean principles adapted for environmental performance. Salvendy (2001) illustrates that IE practitioners possess unique capabilities to bridge the gap between environmental strategy and operational implementation by applying rigorous quantitative analysis, data-driven decision-making, and systemic improvement methodologies. Recognising this potential requires integrating sustainability narratives in a way that enables the discipline to become a central catalyst for organisational sustainability transformations.

2.5 Developing country narrative

Sustainability for developing countries has to consider a stronger reliance on natural resource extraction, technology gaps, financial limitations and inadequate infrastructure (Madu, 1999; Ziaul & Shuwei, 2023). Similarly, IE for developing countries should reorient itself around employment growth, new products and services, education and training as opposed to efficiency and profit (Lister & Donaldson, 2004). The nature and degree of problems differ for developing countries, also warranting higher-order problem solving and innovation using IE.

For developing countries, it is also far more challenging to achieve an SCA due to strategic factors such as skills, rivalry, clustering and policy (Heeks, 2006; Sharkie, 2003). Even TD research in developing countries needs to confront financial constraints, varied technological expertise and conflicting stakeholder perceptions (Mak, 2014).

The synthesis of environmental sustainability, sustainable competitive advantage, transdisciplinary research, and industrial engineering literature reveals a critical research gap. Although circular economy and digital transformation have significantly enhanced how organisations conceptualise and operationalise sustainability, the integration of these paradigms within industrial engineering-led, transdisciplinary contexts remains unexplored, particularly for developing economies. Sustainability

challenges are complex, systemic phenomena whose interconnected economic, environmental, and social dimensions defy compartmentalised problem-solving. Addressing them requires integrating systems thinking to map interconnections (Raworth, 2017), transdisciplinary methodologies to transcend disciplinary silos (Klein, 2008; Nicolescu, 2002), and multi-level strategies to transform governance, business models, and stakeholder engagement (Evans et al., 2017; Loorbach et al., 2017; Stubbs & Cocklin, 2008). While fragmented approaches fail to deliver transformative change, organisations implementing integrated, transdisciplinary strategies achieve superior triple-bottom-line performance by treating sustainability as a holistic systems integration challenge (Lawrence, 2010). Despite the seminal work on environmental sustainability, industrial engineering work and TD artefacts for developing countries, there is still no integrated IE and ES approach that supports an SCA within TD contexts. A comprehensive framework that integrates, co-creates and is contextually developed could unlock transformative pathways for developing nations to achieve simultaneous environmental and economic resilience for an SCA.

3. Research methodology

3.1 ACD Methodology

This research incorporates an established design methodology by Roopa (2024) for TD problem solving and sustainable development for developing countries. This methodology facilitated the development of an Industrial Engineering lighthouse model for strategic foresight, incorporating Sustainable Development Goals (SDGs). The methodology is structured such that high-level abstraction facilitates problem-oriented results similar to Gregor *et al.* (2013). The use of this methodology created a TD artefact. This process ensures theory development during abstraction, which is to be further contextualised before the design process is initiated. These three stages are visualised in Figure 1.

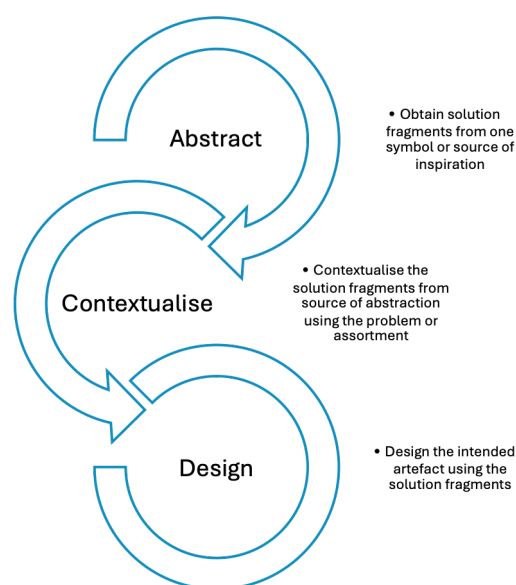


Figure 1: ACD methodology adapted from Roopa (2024)

At the beginning of the ACD methodology, a symbol or source of inspiration is used as a metaphor to create a transdisciplinary artefact. Once achieved, the next task is to harness set functions or requirements that can be used for the solution fragments. As emphasised by Hoover *et al.* (1991), abstraction serves as a critical approach that guides design decisions by simplifying the complex relationships that constitute a problem.

The contextualise phase serves as the intermediary phase, which houses the various characteristics unique to or case-specific by subject matter, geographical region or method of application associated with the problem. There are two possibilities for contextualisation. The contextualisation can be made to the problem or the sequencing associated with the solution fragments.

In the final stage, the design process is followed. There is, however, no prescribed design logic, a shortcoming later addressed in this research using the argued cascading knowledge stream from the results. The TD solution is created using the symbol of inspiration and solution fragments in the abstraction and contextualisation stage. However, the design must adhere to the requirements and be an inherent feature.

3.2 ACD adaptation

An adaptation of the ACD methodology is employed in this research. Sources of qualitative research are clustered into the three business execution levels, which entail strategic, tactical and operational tiers (Ross *et al.*, 2006). For this research, the integrated industrial engineering and environmental sustainability strategies, theories, methods and practices will be placed within these three tiers. Using structured text condensation, the first qualitative data consists of 25 research papers obtained from the Systematic Literature Review findings from Roopa *et al.* (2024). The second data source stems from 24 interviews with industrial engineers or environmental managers and practitioners who work in South Africa. This condensation technique allows cross-case analysis of various data types (Malterud, 2012). Therefore, it is deemed appropriate given the nature of the two qualitative data sources.

A newly coined technique is claimed in this research, a Pareto-Weighted Thematic Analysis (PWTa). This is employed by using the coded results from the text-condensation. Having found inspiration from the seminal work of Buetow (2010) and Northcutt and McCoy (2004), weighted factors are added to the data by quantitising this cumulative dataset. Quantitising denotes the numerical translation of qualitative data so that it can be counted, ranked before applying a threshold (Sandelowski *et al.*, 2009). The PWTa first extracts code densities by calculating the total code density per formulated theme. Next, the data is ranked from highest to lowest density within each coded element. The cumulative percentage of the combined quantitised qualitative data is then computed. Thresholding is finally applied to identify the “Vital Few” themes as opposed to the “Trivial Many” as detailed by Juran (2003). This abides by Pareto’s principle, arguing in this research that 20% of the themes (and elements) carry 80% of the weight or relevance.

The coding procedure is reported here for transparency. Codes were generated inductively from the text-condensed literature and interview material by the first author,

who compiled a codebook recording each code, its definition and exemplar excerpts. A formal inter-coder reliability statistic was not computed, consistent with guidance that such statistics are not always appropriate where coding is concept-driven and consensus-based (McDonald et al., 2019; O'Connor & Joffe, 2020); qualitative trustworthiness was instead pursued through the audit trail presented in Table 1, which records every consolidation decision and its rationale.

The 80/20 threshold is applied as a managerial heuristic rather than a statistical law. Its use is supported by evidence that the Pareto principle holds across a wide range of organisational decision contexts (Craft & Leake, 2002; Grosfeld-Nir et al., 2007), and code frequency is treated as a proxy for the salience of a concept across sources, following the saliency-analysis logic of Buetow (2010). Two safeguards address the risk that frequency-based filtering omits low-frequency but theoretically important constructs. First, the interviews served as a contextual refinement step where components that practitioners emphasised were retained and, where necessary, reclassified irrespective of their literature frequency. This is recorded in Table 1. Second, filtered components are excluded from the sides of the framework but not discarded from the dataset, so that alternative configurations remain recoverable given the Zwicky box application discussed in section 3.2.4. Nonetheless, this research acknowledges that treating the most frequent themes as the most relevant for a sustainable competitive advantage is a methodological choice.

By pre-emptively reviewing the qualitative data sets, design requirements are formulated in the abstraction phase to support the development of a framework that harnesses IE and ES knowledge for an SCA. This phase of the ACD methodology is cognisant of the diverse knowledge obtained. To standardise and cluster this diverse knowledge, an application stream will be applied across the three business execution levels. An application stream is defined here as an ordered sequence that links a selected strategy to its supporting theories and, in turn, to executable methods and practices across the strategic, tactical and operational levels strictly top-down.

3.2.1 Reliability, validity and sample size of data

Although there is debate concerning the classification of reliability in qualitative research (McDonald et al., 2019), reliability builds trustworthiness, consistency and accuracy in the results by maintaining rigour through verified strategies integrated in the research process (Morse et al., 2002). In the ACD methodology adaptation, the text condensation forces pairing of reliable data sources where the SLR employed the PRISMA checklist, whereas the interviews followed the protocol advised by Creswell and Creswell (2017). On the other hand, validity can be defined by the credibility, authenticity, criticality and integrity of the data that incorporates rigour and subjectivity (Whittemore et al., 2001). The research holds true to credible literature and interview data combined. According to Schultze and Avital (2011), authentic and rich data is normally obtained from interviews. Criticality is applied by the PWTA reduction. As for integrity, the reliability of the data already professed holds in this instance. In addition, a single coder was used for consistency, which was paired with the aforementioned strategies to ensure reliability in the data.

In qualitative research, the sample and population size can be a function of saturation, which determines when data collection should stop (Leese *et al.*, 2021). The relationship between the present study and the prior systematic literature review warrants explicit clarification. This study furthers the work from Roopa *et al.* (2024), by applying the corpus as its literature dataset of 25 publications using a Systematic Literature Review. That corpus was deemed sufficient because it was compiled under the PRISMA protocol with the explicit purpose of mapping IE and ES knowledge. The very constructs integrated here, and a supplementary scan of publications appearing after the review period was undertaken to confirm that no subsequent contribution materially altered the identified knowledge components.

The interview dataset comprises 24 practising industrial engineers and environmental managers or practitioners based in South Africa, recruited through purposive snowball sampling across multiple industrial sectors from a study executed by Roopa and Siriram (2026). This second dataset contained stop criteria from Francis *et al.* (2010), arguing data saturation. The stop criteria were such that three additional interviews occurred when code frequencies were reached for a knowledge component and when participants referred to already interviewed participants, given the purposive snowballing technique employed. Participants were selected based on their direct professional involvement in sustainability-oriented improvement initiatives, ensuring their relevance to this research.

3.2.2 Abstraction

The inspiration for this research begins with abstraction from nature, similar to Biomimicry, which emulates nature's genius by incorporating its innovative traits and time-tested solutions (Benyus, 1997). Nature is sustainable. The first frame of reference is to perceive environmental sustainability as a burning issue, symbolising fire. A force more powerful than fire is water. Wisniak (2004) also argues that water plays a foundational role in the universe and is often associated with creation and life. The properties of the water metaphor map onto the research problem as follows:

1. Hierarchy: the pyramid's tiers correspond to the strategic, tactical and operational business execution levels
2. Flow and sequencing: the downward cascade represents the ordered selection from strategies to theories and then to methods and practices
3. Filtering: The PWTA acts as a filter, retaining the vital few knowledge components from the trivial many
4. Confluence and integration: The merging of IE and ES knowledge streams mirrors tributaries joining a river system.

A pyramid alone conveys hierarchy, but none of the flow, filtering or feedback properties; the water metaphor therefore carries the dynamic semantics of the framework. The conceptual implication of combining the two water behaviours is that the framework is simultaneously prescriptive (top-down cascade) and adaptive (recirculating feedback); the managerial implication is that adopting organisations must institutionalise both a selection routine and a learning routine, and the limitation is that the metaphor structures, rather than proves the underlying relationships.

Next, it is important to consider the downward flow of water, similar to the application streams for organisations that begin with a strategy, turn to theory and execute changes using methods and practices across the three business execution levels. This solution stream promotes coherence between IE and ES knowledge in support of an SCA. In nature, water achieves this movement and meets other forms of water in a river system. Water can represent knowledge to build on the analogy and blueprints for the TD framework. Another important aspect of this phase is to sketch design requirements. The requirements are formulated using systems thinking, interpretivist systems, and a morphological box discussed in the design phase.

3.2.3 Contextualisation

The various sources of knowledge components from the SLR and interviews are combined by quantitising, pairing and applying the PWTA previously discussed. This allows for contextualised solution fragments that support an SCA in conjunction with the water analogy.

The cascading application of knowledge follows a water analogy that begins with a top-down approach since this naturally reduces the number of possible combinations, given that strategies have the lowered tiered classification. This transcends directly across the business execution levels. Furthermore, the strategies are the initial phase in achieving a sustainable competitive advantage. To paraphrase Kapsali (2022), a top-down design approach for environmental sustainability can address complex issues by creating integrative perspectives with the bottom-up engineering insights. Alluvial (top-down) and sunburst diagrams (bottom-up) are also used to inform the design, as discussed further in section 4.

3.2.4 Design phase

Systems thinking was an emergent theory that featured in the text condensation process. Systems thinking is an integrative and holistic approach that identifies patterns and relationships in complex systems that contain dynamic patterns of change (Caulfield & Maj, 2001; Monat & Gannon, 2015). As elucidated by Darwish (2018), Alman (2014) defines a hierarchy of causal relationships reproduced in Figure 2.

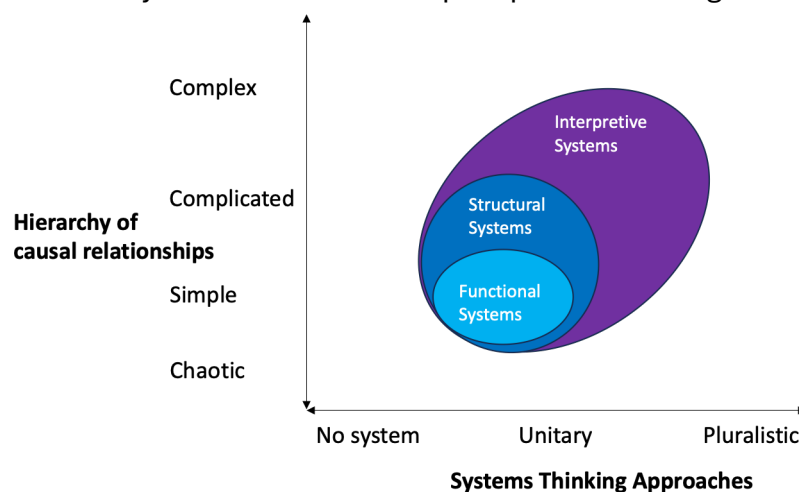


Figure 2: Systems Thinking Maturity Model redrawn from Alman (2014)

An interpretive system can handle “messy” or complex problems that have unpredictable causes and effects, owing to causal relationships that become visible over time (Alman, 2014). It is for this reason that an interpretive system will be designed to demonstrate flow between the various strategies, theories, methods and practices. The consideration of a morphological (Zwicky) box also influenced the design's nature. A morphological box is a tool used to generate creative solutions that explore possible combinations of parameters that lead to innovative solutions (Bartels *et al.*, 2024). In this research, this representation is provided in Figure 3 by showcasing the intersections between the three forms of knowledge components classified in this study.

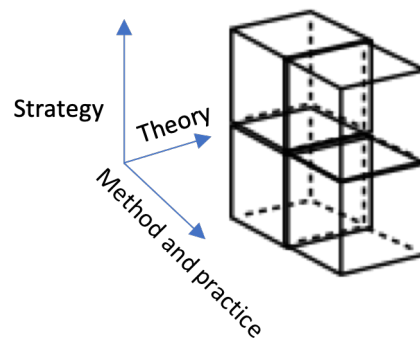


Figure 3: Morphological representation of knowledge components

The structure of the intersection demonstrates organisational enablers that facilitate the transition between strategic, tactical and operational levels. The shortcoming of this representation is that it does not account for downward flow of knowledge, arguing that one needs to move in a direction that can only exist in a fourth dimension, and that each knowledge component is orthogonal to the others. This representation also suggests that the application streams are at intersections of the Zwicky box. However, the advantages of this structure demonstrate complex interactions that motivate the simultaneous and multiple use of sustainable competitive advantage pathways at similar or varying levels. Section 4 foreshadows this methodology by structuring the results and findings according to the data consolidation process, visualisations and TD artefact.

3.3 Confirmatory Focus Group (CFG)

Focus groups are established qualitative techniques in the social sciences used to explore ideas, evaluate artefacts through exploratory focus groups (EFGs), or confirm field utility via confirmatory focus groups (CFGs) (Monica Chiarini *et al.*, 2010; Morgan, 1996). Designed to gather rich, direct interaction faster and more cost-effectively than isolated methods (Mazza & Berre, 2007), focus groups are frequently combined with surveys (Morgan, 1993; Morgan, 1996). Their execution hereof depends heavily on study aims, questions, and duration (Tang & Davis, 1995), with group sizes typically ranging from 4 to 12 participants to prevent both social loafing and over-participation (Monica Chiarini *et al.*, 2010; Morgan, 1996). This research operationalises CFG in Design Science Research, abiding by the five-step framework from O'Raghallaigh *et al.* (2012).

This study applies a single 1.5-hour online CFG to evaluate the TD framework artefact, integrating simultaneous online Likert-scale survey polls to mitigate the complexity of

open-ended analysis (Poliandri *et al.*, 2023; van der Linde & Roopa, 2021). To prevent participant fatigue and disengagement (Braun *et al.*, 2021; Mazza & Berre, 2007), the agenda comprises a 10-minute introduction, 75 minutes of discussion and polling, and a 5-minute conclusion. The panel reconvenes the experienced transdisciplinary sample from the initial interviews from Roopa and Siriram (2026), however limited to 10 participants in order to leverage preceding expertise while maintaining manageable group dynamics (Monica Chiarini *et al.*, 2010). Serving as the unmediated researcher, this form of moderation fosters organic discussion and minimises structural constraints (Schmidt & Hunter, 1978; Schwarz, 1994). Furthermore, confirmation bias is controlled via targeted open-ended questions (Schneider, 2000) (Schneider, 2000), capped at two minutes per contribution. In addition, pseudo-anonymised session transcripts ensure analytical rigour (Roopa, 2021). The study was conducted under ethical clearance granted by the North-West University, Faculty of Engineering Research Committee (NWU-ENGREC) with the ethics code NWU-00235-23-A3.

4. Results and findings

4.1 Data consolidation

As discussed in section 3, the ACD methodology led to the abstraction of water along systems thinking, interpretivist systems and morphological representation. In the contextualisation phase, the data consolidation removed duplications and contradictions.

4.1.1 PWTA application

To amalgamate the results, the data from the preceding stages of the research were placed into three clusters, IE, ES and IE-ES integrated as one concept. The consolidation of this contains a total of 224 knowledge components. This entails two clusters from the SLR, namely industrial engineering (IE-x) and environmental sustainability (ES-x). The x denotes the relevant knowledge component at the specific business execution level. These two clusters see the link as siloed hubs of knowledge. The third cluster is the collective industrial engineering and environmental sustainability (IE-ES x) clustering retrieved from the interviews.

During the consolidation and filtering of knowledge components, duplications emerged. These were removed in cases where a concept repeated itself within the same business execution level. Each literature paper element or interview element coded was allocated a weight of one. The total frequency combines the total knowledge component weighting to preserve its weight. This is merged with the outcomes and rationale feature in Table 1.

Table 1: Knowledge component filtration and consolidation summary

Concept (Final Term)	Final Cluster	Frequency	Key Changes/Consolidation
1. Systems thinking	IE-ES Strategy	4	Reclassified from Strategy/Theory to IE-ES Strategy

Concept (Final Term)	Final Cluster	Frequency	Key Changes/Consolidation
2. Cleaner and safer production	ES Strategy	1	Removed "Clean production" and retained the more collective ES Strategy term
3. Corporate social responsibility (CSR)	IE-ES Strategy	3	Used the more generic CSR term, consolidating it with "Corporate sustainability"
4. Cradle to Cradle (C2C)	IE-ES Theory	3	Retained the pre-emptive C2C over "Cradle to grave" to promote circularity
5. Circular economy (CE) and sharing principles	IE-ES Strategy	13	Condensed into one collective IE-ES Strategy term
6. Design for Environment (DFE)	IE-ES Theory	2	Principles seen as synonymous; consolidated as a collective IE-ES Theory
7. Efficiency	IE-ES Strategy	7	Used the generic term Efficiency but migrated it to a collective IE-ES Strategy
8. Environmental Management	ES Strategy	5	Umbrella term encompassing EMS, monitoring, protection, and management
9. Facility design	IE-ES Theory	4	Umbrella term encompassing process design and planning, re-affirmed as a collective theory
10. Fishbone diagram	IE-ES Method/Practice	4	Consolidated as a collective IE-ES Method/Practice
11. Game theory	IE-ES Theory	2	Combined as a collective IE-ES Theory from separate IE and ES theory instances
12. Prevent Greenwashing	IE-ES Method/Practice	3	Combined and rephrased as Prevent Greenwashing within IE-ES Method/Practice
13. Industrial ecology	IE-ES Theory	2	Merged as the only form of transdisciplinary

Concept (Final Term)	Final Cluster	Frequency	Key Changes/Consolidation
			knowledge into IE-ES Theory
14. Lean and Green	IE Theory	16	The lexicon was shifted to Lean and Green, though the primary focus remains on IE Theory traits
15. Machine Learning	IE Theory	9	Migrated to IE Theory despite one IE-ES mention, due to it being a core IE concept
16. Product design and regeneration	IE-ES Strategy	3	Chosen for its environmental sustainability traits and condensed as an IE-ES Strategy (Item 16).
17. Risk management	IE-ES Theory	3	Consolidates various forms into a collective IE-ES Theory (Item 17).
18. Simulations	IE-ES Strategy	10	Amalgamated into IE-ES Strategy (a theory to strategy migration) (Item 18).
19. Supply chain (management)	IE-ES Theory	9	Modified to a collective IE-ES Theory based on participant input
20. Triple Bottom Line (TBL)	IE-ES Strategy	4	Amalgamated People, Planet, Profit and TBL into the TBL strategy (Item 20).
21. Supply chain evaluation	IE-ES Strategy	1	Modified from ES Strategy to a collective IE-ES Strategy
22. Technology and innovation	IE-ES Strategy	7	Combined into an IE-ES Strategy
23. Value engineering	IE Theory	6	Condensed to Value engineering and updated the frequency
24. Decision support systems (DSS)	IE-ES Strategy	4	Rephrased to DSS to encompass data-driven decision-making and data analytics within IE-ES Strategy

The PWTA was employed and deemed appropriate after already being applied in organisational contexts (Craft & Leake, 2002). The cumulated weight is recalculated

before applying Pareto's principle for each pairing sequentially in a top-down approach across the three tiers of the business execution levels. This data consolidation and reduction resulted in a decrease in knowledge components from 234 to 197. During the ranking process, 13 of these from the SLR from Roopa *et al.* (2024) could not be classed within the IISE (Institute of Industrial and Systems Engineering) body of knowledge areas. The PWTA application on the quantitised codes resulted in a further reduction of 197 to 107 knowledge components. A summary of the data consolidation PWTA application is visualised in Figure 4. M&P denotes methods and practices, and the classifiers conform to those previously defined before being truncated and filtered. Ultimately, this led to the configuration of the TD framework presented in section 4.2.

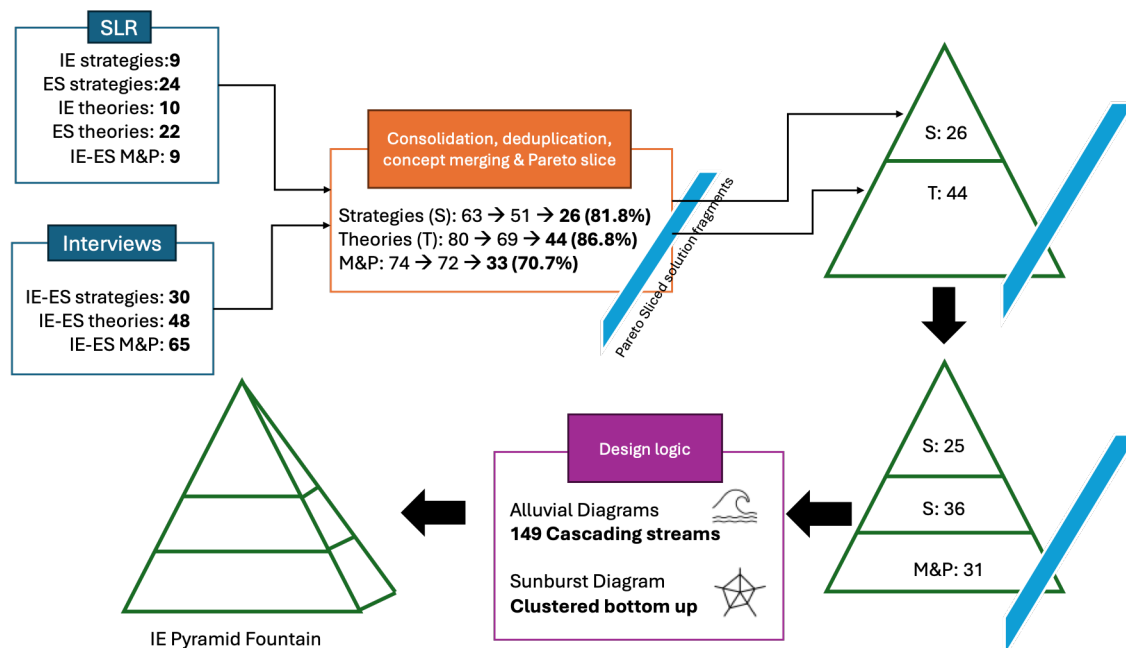


Figure 4: Visualised data consolidation and design process employed

Alluvial diagrams are used to demonstrate the hierarchical structure (Liu *et al.*, 2013), evidencing a top-down flow of knowledge. The alluvial diagrams should be read as follows: each column represents a knowledge component class (strategies, theories, and methods and practices), each block represents a component, and the height of a ribbon represents the cumulative code density linking two components; thicker ribbons therefore denote more strongly evidenced pairings. The diagrams are dense by design because they document the full evidence base; their role is to render the filtering auditable rather than to serve as stand-alone results. This, together with the PWTA aids in providing appropriate and most effective top-down pairing and clusters (Craft & Leake, 2002). The merging of strategies with theories created 289 new streams that have been clustered and visualised in Figure 5.

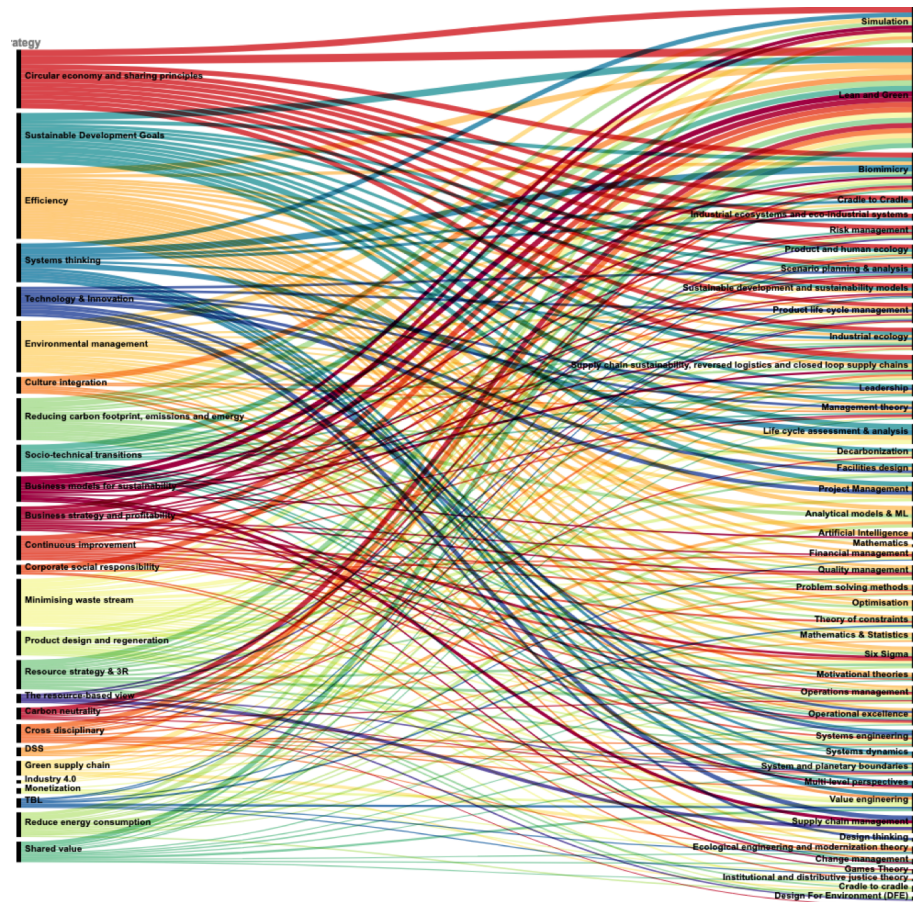


Figure 5: Strategy to theory pairing alluvial diagram

As can be seen, the various strategies speak to many more theories, dispersing the spread of knowledge. The most prevalent strategies are CE and sharing principles, SDGs, efficiency, and minimising the waste stream. These fuse with the concept of Lean and Green, simulation, biomimicry and project management. Another approach to quantify the associations and strength of each strategy and theory combination is to study the cumulative count of each strategy to theory pairing, as summarised in Table 2.

Table 2 : Cumulative density of strategy to theory pairing

Strategy	Cumulated density
Efficiency	255
Circular economy and sharing principles	211
Environmental management	185
Sustainable Development Goals	181
Minimising waste stream	170
Reducing carbon footprint, emissions and emergy	151
Systems thinking	140
Technology & Innovation	106
Resource strategy & 3R	105
Socio-technical transitions	97
Business models for sustainability	92

Strategy	Cumulated density
Continuous improvement	89
Product design and regeneration	89
Reduce energy consumption	89
Business strategy and profitability	88
Shared value	74
Cross disciplinary	67
Culture integration	60
Green supply chain	53
Carbon neutrality	41
Corporate social responsibility	34
TBL	34
The resource-based view	33
DSS	32
Monetisation	20
Industry 4.0	12
Grand Total	2 508

To truncate the results further, PWTa is applied to the strategy and theory pairings. This reduced the 289 combinations to 184, such that the remaining combinations can now be clustered with appropriate methods and practices for the last business execution level used to create Figure 6. This demonstrates the pairing of the Pareto-weighted strategies and theories with the various methods and practices and consolidated knowledge component pathways. This expanded the number of application streams from 184 combinations to 200. The representation of these is provided in the alluvial diagram. The weakest flow and lowest densities are found to be the ecological engineering theory and carbon tax; the polluter pays principle and recycling are the lowest methods and practices. A vast majority of the knowledge streams stagnated and could not be matched with the “none” category. This implies that none of these matched the PWTa methods and practices.

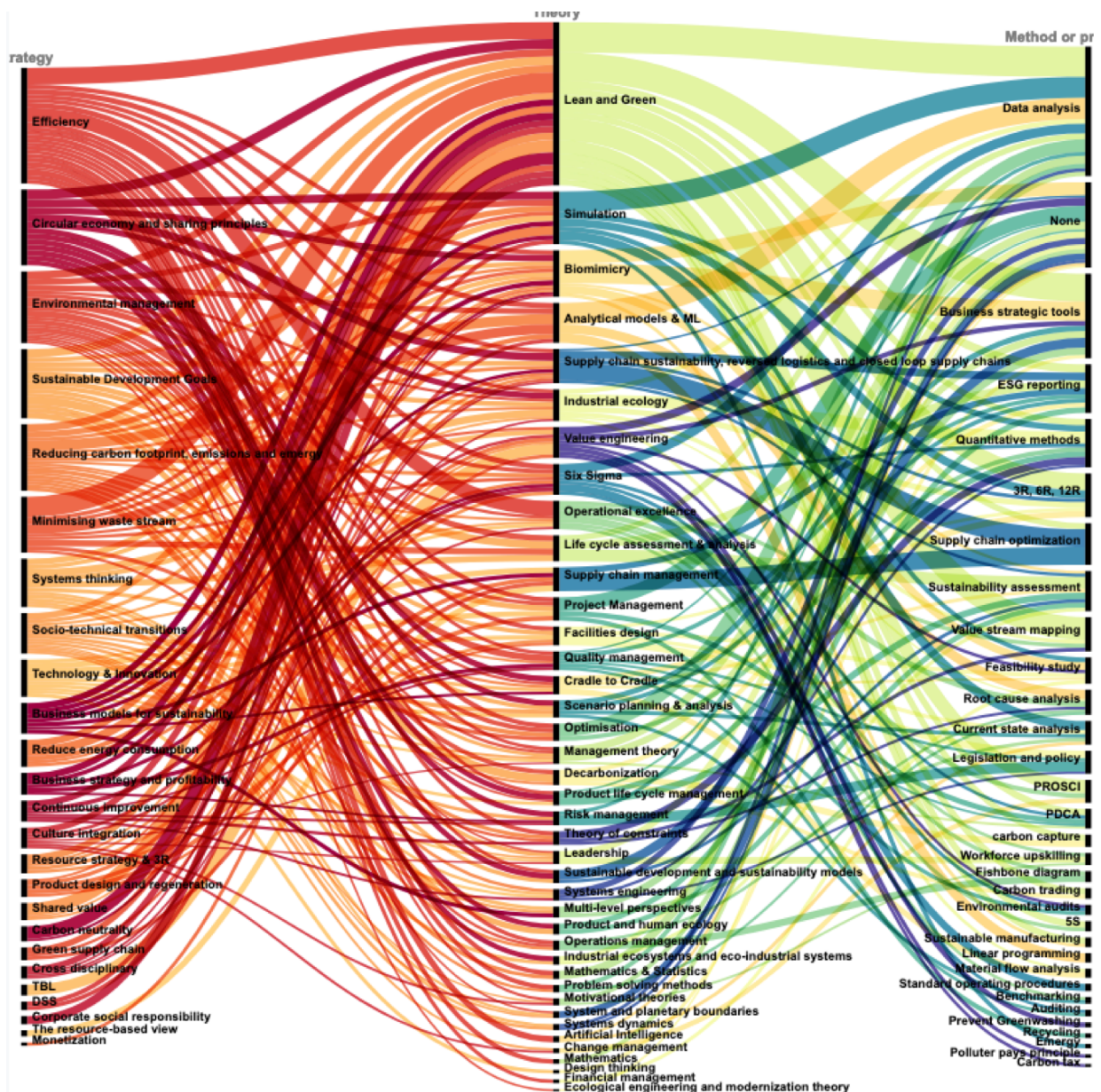


Figure 6: Knowledge component pathway pairing alluvial diagram

Much of the knowledge flows towards data analysis and business strategic tools. This alludes to business contexts and strategic direction that the various tools can render, but also the necessary data analysis that is needed in order to achieve a SCA. Although many of these strategies, theories and methods and practices show the vast majority of knowledge streams that can exist, this is still convoluted thus necessitating a final PWTA application. The final PWTA slice has been performed in Figure 7 which has also removed the “None” component. This presents the final alluvial diagram as part of the contextualisation phase.

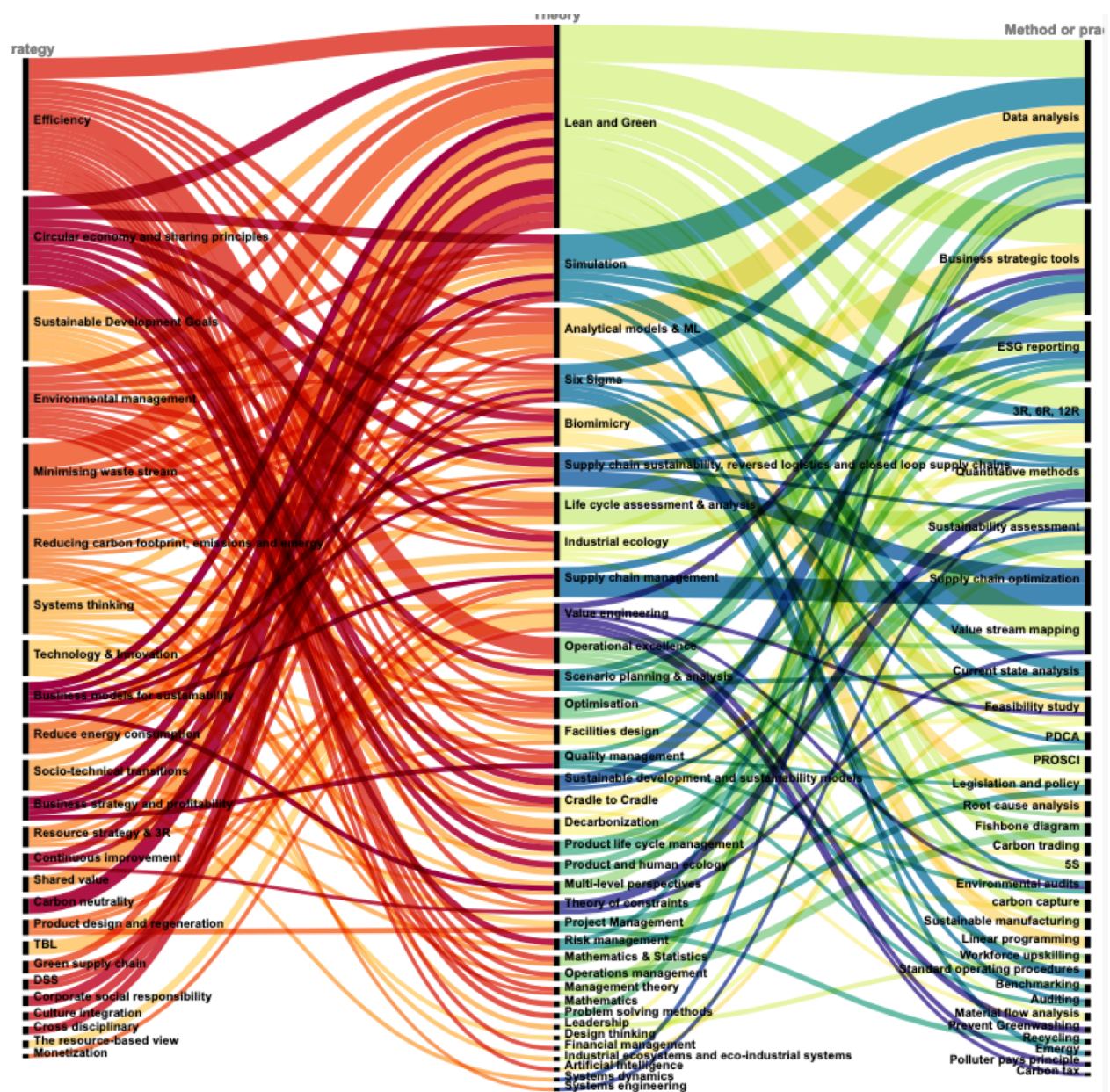


Figure 7: PWTA knowledge component pathways

ESG reporting, 3R, 6R and 12R and quantitative methods are among the most common methods and practices that feature as the final steps in achieving a sustainable competitive advantage.

4.1.2 TD artefact structure

Using the contextualised data and design logic, the cascading effect of the knowledge components is embedded into a pyramid structure that resembles the business execution levels. Each knowledge component is clustered according to the PWTA, contextualised alluvial and sunburst diagrams that have been based on the solution fragments that have been subjected to PWTA and contextualised. The design phase serves as the final stage in the ACD methodology discussed in the following subsection. This ultimately led to an analogy with a pyramid fountain, coined the Industrial Engineering pyramid fountain for environmental sustainability and a sustainable competitive advantage. This adheres to the aforementioned requirements while serving

as an interpretative system that also shares connotations with a morphological box representation.

Figure 8 provides the dissection of the pyramid water fountain framework, which comprises four sides on which to model and place certain strategies (green), theories (yellow) and methods and practices (orange). At the top centre of the fountain is the knowledge core that entails IE (white), ES (grey) and SCA (red).

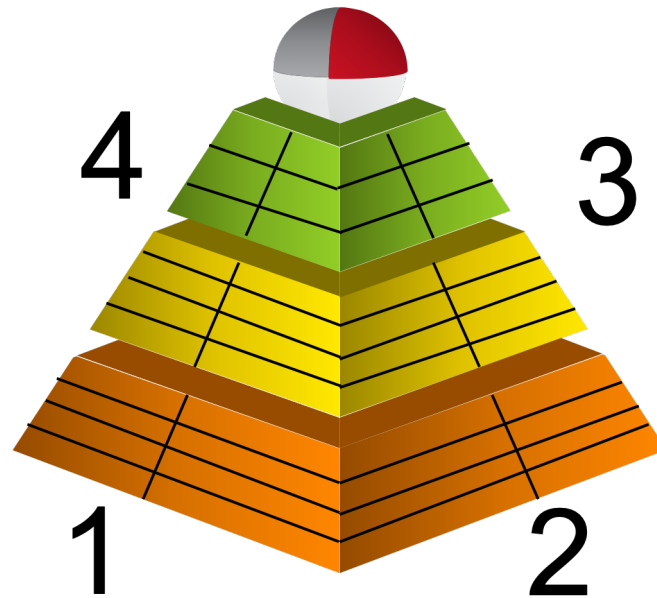


Figure 8 Pyramid water fountain side allocations

The dissection incorporates the Zwicky box analogy, water that flows down each side of the pyramid and into the knowledge core. The filtering of the data led to a reduction of 25 strategies, 36 theories and 31 methods and practices. This composition led to the clustering and representation of 6 strategies, 8 theories and 8 methods and practices on each of the four labelled sides of the pyramid, segmented using Table 3.

The allocation of knowledge components to particular sides was not arbitrary. Components were assigned according to three rules:

- I. co-occurrence where strategies, theories and methods that exhibited the strongest pairing densities in the alluvial and sunburst analyses were placed on the same side;
- II. thematic coherence given that each side was constructed around a recognisable orientation, namely efficiency and business performance (side 1), systems and supply chain thinking (side 2), quantitative and life-cycle techniques (side 3), and carbon management with continuous improvement (side 4) and
- III. Balance considering that sides were constrained to approximately six strategies, eight theories and eight methods and practices so that each face remains navigable.

It is acknowledged that alternative configurations were plausible, however the configurations presented are best supported by the observed pairing densities according to the PWTA.

Table 3: Knowledge component configurations

Strategy 1	Strategy 2
Strategy 3	Strategy 4
Strategy 5	Strategy 6
Theory 1	Theory 2
Theory 3	Theory 4
Theory 5	Theory 6
Theory 7	Theory 8
Method and practice 1	Method and practice 1
Method and practice 3	Method and practice 4
Method and practice 5	Method and practice 6
Method and practice 7	Method and practice 8

4.2 TD artefact

An important way of clustering all of the densities is through a bottom-up hierarchical representation that can be achieved using a sunburst diagram. Sunburst diagrams are able to demonstrate hierarchical structure differently to tree-maps and alluvial diagrams (Stasko *et al.*, 2000). Figure 9 shows the clustering of the methods and practices at the inner circle, theories in the middle, and strategies in the outer circle with a bottom-up approach, unlike previous alluvial diagram visualisations.

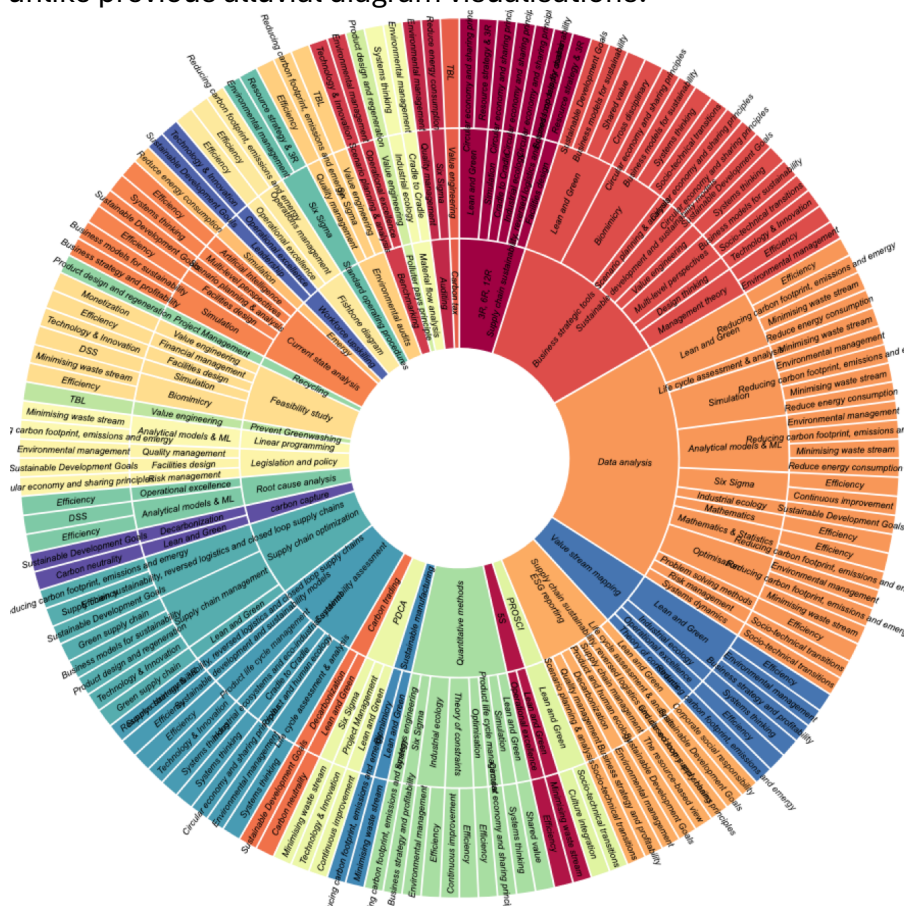


Figure 9: Sunburst diagram of the knowledge components

As can be seen, various efficiency-related strategies resonate with data analysis. For the specific methods and practices such as carbon capture, it can easily be traced back to decarbonisation and lean and green theory, which are linked to SDGs and carbon

neutrality. To cluster this further, the reduction of energy consumption, carbon footprint, emissions and energy were merged into one concept. Theories were also reduced from 36 to 31, merging aspects such as mathematics with statistics. Next, side selections and categorisations are determined. The side configurations test the top-down design from the alluvial diagrams, in comparison with the bottom-up articulation the sunburst diagram provides. This bi-directional categorisation led to the four side configurations for the artefact, given commonality and strongest associations to drive the approximation between each knowledge component. The first configuration for one of the sides of the pyramid fountain is provided in Table 4.

Table 4 Knowledge component arrangement for side 1 of the pyramid fountain framework

Efficiency	Business strategy and profitability
Business models for sustainability	Circular economy and sharing principles
Resource strategy & 3R	Corporate social responsibility
Simulation	Lean and Green
Six Sigma	Operational Excellence
Operations management	Theory of Constraints
Biomimicry	Financial management
Data analysis	Business strategic tools
3R, 6R, 12R	Value stream mapping
5S	PROSCI
Legislation and policy	Supply chain optimisation

Table 4 provides a more detailed examination of efficiency and business performance. It also considers the inclusion of CE for strategic intent. This side contains the more dominant knowledge streams that emerged from the alluvial diagrams and are supported by the various theories that share strong associations with IE. The execution hereof incorporates data analysis and value stream mapping. Notably, it also features supply chain optimisation, which aligns with and complements side 2, as showcased in Table 5.

Table 5 Knowledge component arrangement for side 2 of the pyramid fountain framework

Green supply chain	Sustainable Development Goals
Socio-technical transitions	Cross disciplinary
Systems thinking	Monetisation
SCM, reversed logistics and closed loop SC	Product life cycle management
Multi-level perspectives	Project Management
Systems dynamics	Systems engineering

Leadership	Product life cycle management
Industrial ecosystems and eco-industrial systems	Product and human ecology
ESG reporting	Feasibility study
Prevent Greenwashing	Fishbone diagram
Workforce upskilling	Sustainability assessment

The 2nd side of the pyramid fountain entails more holistic and systems thinking aspects portrayed by supply chain, systems thinking and ESG reporting. It also has certain management theories that complement sides 1 and 3 of the pyramid fountain. These two sides present the first side of the pyramid, as demonstrated in Figure 10.

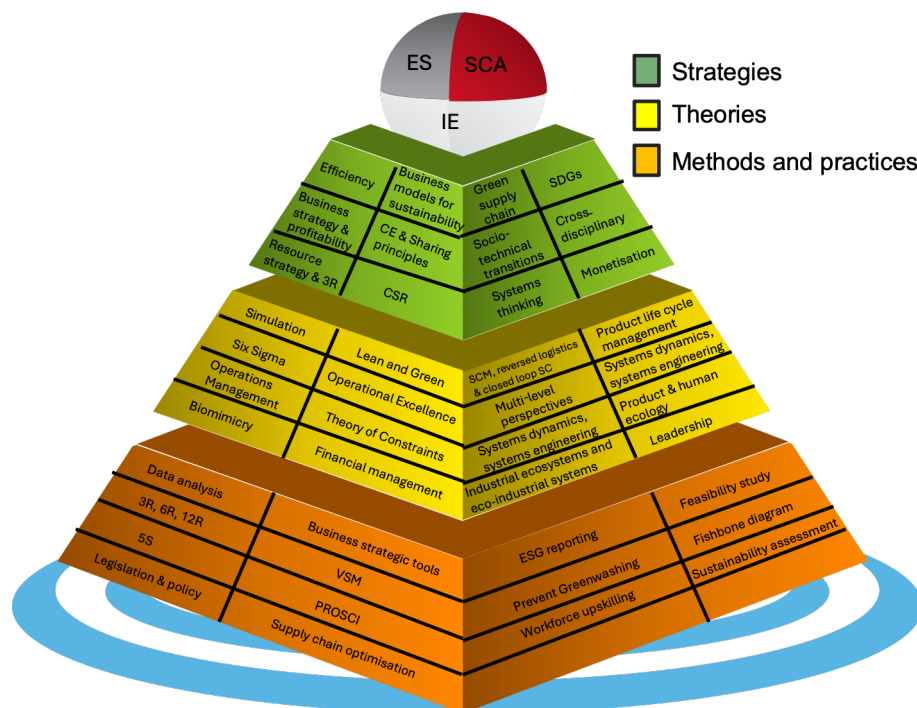


Figure 10 Pyramid fountain framework side 1 and 2 representation

In order to use the framework, the organisation first selects their intended strategy through engagement and consensus transparently obtained within the organisation. Theories precede the selection of a method or practice. Side 2 of the pyramid is the only side with more theories, having a total of 10 theories selected. This was due to the configuration and links with sides 1 and 3 that required more of the clustered theory on its adjacent side. It has been balanced by having fewer methods and practices that still adhere to the structure of the alluvial and sunburst diagrams. Table 6 now presents the knowledge components belonging to side 3.

Table 6 Knowledge component arrangement for side 3 of the pyramid fountain framework

Minimising waste stream	DSS
Shared value	Resource-based view

TBL	Product design and regeneration
Industrial ecology	Value engineering
Product life cycle management	Mathematics & Statistics
Scenario planning & analysis	Optimisation
Sustainable development and sustainability models	Life cycle assessment & analysis
Current state analysis	Quantitative methods
Material flow analysis	Recycling
Root cause analysis	Polluter pays principle
Standard operating procedures	Sustainable manufacturing

The undertone of this side of the pyramid fountain is more geared towards quantitative techniques and life cycle assessment. This also contains industrial ecology which is further supported by systems thinking, cross-disciplinary strategic intent and ecology. This side also contain various analysis techniques that best minimise the waste stream demarcated in Table 7 contains the remaining knowledge components.

Table 7 Knowledge component arrangement for side 4 of the pyramid fountain framework

Carbon neutrality	Continuous Improvement
Technology & Innovation	Environmental management
Culture integration	Reduce carbon footprint, emergy and emissions
Quality and risk management	Design thinking
Problem solving methods	Facilities design
Decarbonisation	Cradle to Cradle
Management theory	Artificial Intelligence
PDCA	Carbon tax
Auditing	Carbon capture
Carbon trading	Benchmarking
Environmental audits	Emergy

Side 4 contains carbon neutrality, which is achieved by decarbonisation and through procedures such as carbon trading and sequestration. The continuous improvement strategy also complements side 1, which contains the various efficiency-oriented theories. Sides 3 and 4 can be combined to provide the representation of the opposite side of the IE pyramid fountain with Figure 11.

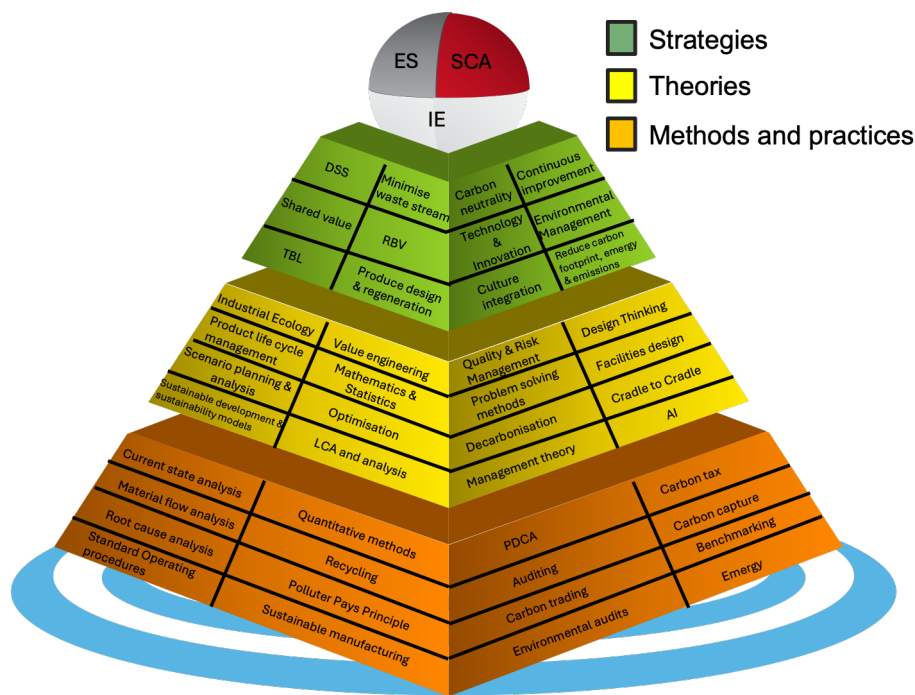


Figure 11: Pyramid waterfall framework side 3 and 4 representation

These four sides of the pyramid create a multi-dimensional method of supporting an SCA by following the application stream along either side of the framework. It begins by selecting the strategic intent. This uses pertinent theory adjacent to the strategic side of the framework. At an operational level, the specific methods and practices can be selected to execute the organisational objective. Once achieved, the new knowledge can be used to internalise the learning and experiences within an organisation in achieving an SCA.

4.3 Confirmatory Focus Group results

During the interaction, participants were coded as focus group participants (FGP) one until the six who partook in this stage of the research. The following table provides the results from survey statements posed after demonstrating the Pyramid waterfall framework to the participants.

Table 8 CFG survey results

Survey statement	Respondent						Descriptive statistics	
	FGP1	FGP2	FGP3	FGP4	FGP5	FGP6	Average	Standard deviation
ST1. Research problem: The knowledge of industrial engineering and environmental sustainability currently remains disconnected with organisations unable to successfully adopt environmental sustainability	5	4	4	4	2	4	3.8	0.98

Survey statement	Respondent						Descriptive statistics	
	FGP1	FGP2	FGP3	FGP4	FGP5	FGP6	Average	Standard deviation
for a sustainable competitive advantage in South Africa.								
ST2. The framework demonstrates knowledge that is from industrial engineering	5	5	5	5	5	5	5.0	0
ST3. The framework demonstrates knowledge that is from environmental sustainability	4	5	4	4	5	5	4.5	0.55
ST4. The framework demonstrates cascading and aligns with the business execution levels	4	5	4	4	4	5	4.3	0.52
ST5. The framework demonstrates mechanisms to ensure a sustainable competitive advantage in South Africa	5	5	3	4	3	4	4.0	0.89
ST6. The framework addresses the research problem	5	5	5	5	4	5	4.8	0.41
						Grand mean:		4.5
						Average standard deviation:		0.5

These quantitative results indicated high acceptance and strong consensus with a mean of 4.5 and an average standard deviation of 0.5. This is also joined by a unanimous score of 5 for statement two, associating the TD artefact with Industrial Engineering, and that framework accurately embodies Industrial Engineering (IE) knowledge in a way that successfully drives transdisciplinary integration via the PWTA.

A major discussion point focused on the framework's cascading and reticulating design logic. While FGP2 praised its practical clarity, FGP6 queried whether the framework captures the upward flow of operational learning back to strategic orientation. FGP4 expanded on this by proposing a "pump mechanism" to represent the methodological steps that reverse-engineer sustainability initiatives (e.g., carbon footprinting) back to SDG alignment. Drawing on thermodynamic principles, FGP1 introduced an entropy analogy, arguing that downward-cascading knowledge loses energy unless actively replenished via feedback. This entropy perspective aligns directly with research from Du Preez and Louw (2007) on knowledge supply chain model. This is orientated around

knowledge obsolescence across domains. It also aligns with the SECI knowledge spiral (Nonaka & Takeuchi, 1995). Consequently, the reticulation mechanism transforms the model into an adaptive instrument rather than a static prescriptive tool.

The dialogue also highlighted the transdisciplinary duality and strategic significance of the TD artefact. FGP5 noted a fundamental duality in interpretation, whether it is sustainability brought into industrial engineering contexts (FGP1), or vice versa (FGP5). This was resolved around the point that achieving either confirms a transdisciplinary artefact has been produced. FGP1 emphasised that engineering and conservation are traditionally siloed, arguing that engineers and environmental scientists must innovate with each other rather than for each other. This ethos echoes the Natural-Resource-Based View's (NRBV) product stewardship requirement for stakeholder integration. Addressing implementation barriers, FGP6 recommended further research into organizational skills acquisition to build dual IE-sustainability literacy, while FGP3 observed that industry frequently overlooks the synergistic knowledge components that generate sustainable competitive advantage.

5. Discussion and implications

This pyramid waterfall framework is an interpretive system containing integrated IE and ES knowledge. This attests to the work of Seidel *et al.* (2013), who demonstrated how interpretive systems aid organisations with environmental requirements and sustainability practices. Furthermore, this research also addressed TD literature lacking actionable design intuition (Wibeck *et al.*, 2022). In this way, a pragmatic means to achieving SCA is advised using the framework.

The framework transcends system thinking beyond conceptual application by applying soft system perspectives with hard analytical methods, normally with polarity in sustainability science (Caulfield & Maj, 2001).

From the interviews, it was also found that lean (as well as lean and green) has indisputably presented itself as the form of theory with the highest code density. Mangaroo-Pillay *et al.* (2022) created a House of Guidance was created for Lean frameworks, which contain four sets of requirements. The last requirement from their work encourages that frameworks are tested using interviews, case studies of companies, questionnaires, computation and surveys. As previously declared, lean will be paraphrased as lean and green, which shares stronger associations with environmental sustainability. It stands to reason that the framework is grounded in many forms of philosophies and meets this requirement by incorporating interview and literature data.

This research addresses the fragmented knowledge between IE and ES for SCA, with various scholars professing that sustainability-oriented initiatives fail when treated as isolated activities and not integrated (Brough *et al.*, 2020; Perrott, 2014). Furthermore, this reinforces that SCA is dynamic and processual as opposed to static (Rodriguez *et al.*, 2002; Sharma & Gupta, 2024). The continuous nature of the framework aligns with evolutionary traits of innovation for competitiveness (Garud *et al.*, 2013). In addition, the

framework pushes the bounds of the SCA taxonomy from Sołoducho-Pelc and Sulich (2020) by elucidating exact mechanisms that integrate various tools in a TD approach.

The implications of the methodological innovation behind the PWTA approach support hybrid quantitative sustainability research within TD contexts. By quantitising qualitative insights, it boldly contests the notions that sustainability research is descriptive rather than decision-oriented (Buetow, 2010).

This research argues that IE can facilitate TD artefact creation by being a boundary-spanning discipline that can become relevant for developing country contexts (Jesiek *et al.*, 2016; Roopa, 2024). To sidestep the economic pressures and developing country challenges (Eijdenberg *et al.*, 2019), the strong strategic weightings of monetisation, waste valorisation and efficiency suggest sustainability initiatives become more favourable when cast as value-creating opportunities and not regulatory issues (Hart & Milstein, 2003). The CFG attests to empirical evidence for relevance in developing countries, using the South African landscape as a case study.

5.1 Underlying mechanisms and propositions

In response to the need for an analytically grounded account of how the framework generates a sustainable competitive advantage, three underlying mechanisms are made explicit. The first is a knowledge-integration mechanism combining IE and ES components that are otherwise fragmented across disciplines, the framework assembles knowledge configurations that are valuable, rare and imperfectly imitable. These are the traditional antecedents of sustained advantage under the resource-based view (Barney, 1991). The second is an alignment mechanism demonstrating the cascading sequence enforcing vertical consistency between strategic intent, theoretical grounding and operational execution. Thus, this reduces the misalignment that causes sustainability initiatives to fail when treated as isolated activities (Brough *et al.*, 2020). The third is a reconfiguration mechanism: the fountain's recirculation embodies the sensing–seizing–transforming logic of dynamic capabilities, whereby operational learning feeds back into strategic selection under changing environmental and regulatory conditions (Teece, 2007).

These mechanisms yield testable propositions. For the first proposition, organisations that adopt integrated IE–ES application streams will realise greater improvements in combined competitive and environmental performance than organisations applying IE or ES knowledge in isolation. Secondly, the degree of vertical alignment between an organisation's selected strategy, theories, and methods and practices will be positively associated with the persistence of its competitive advantage. Another proposition is that organisations which institutionalise the recirculation step will adapt their application streams more rapidly following environmental or regulatory change. The framework is thereby positioned as a mid-range interpretive approach with falsifiable implications, rather than a formal predictive model, and the empirical testing of these propositions constitutes a priority for future research.

5.2 Positioning and managerial implications

With respect to positioning, the framework complements rather than displaces existing contributions. Relative to meta-analytic and review evidence that sustainability innovation supports competitiveness (Hermundsdottir & Aspelund, 2021; Oduro & Haylemariam, 2025), it supplies the discipline-level integration logic that such studies do not provide. Relative to macro-level strategic sustainability framings from D'amato and Korhonen (2021), it operates at the organisational level of strategies, theories, methods and practices. Relative to the SCA taxonomy of Sołoducho-Pelc and Sulich (2020), it operationalises four of the six clusters while leaving leadership and market orientation for future extension. Complementary or alternative routes, such as maturity models, balanced scorecards or sector-specific roadmaps, remain open to organisations; the distinctive property of the pyramid fountain framework is its transdisciplinary, data-derived and navigable structure. From a managerial perspective, the principal value of the visualisations lies in complexity navigation: the alluvial and sunburst diagrams compress 2 508 coded associations into a finite set of application streams, and the pyramid's four sides convert this evidence base into a structured approach that decision-makers can traverse without engaging with the underlying diagrams. This warrants policy implications to be positioned at a national and firm level, consistent with SCA literature.

A well-established TD model from Lang et al. (2012) spans collaborative problem framing, co-production of knowledge, and (re)integration into practice. When contrasting this with the TD artefact in this research, it satisfies the first two phases through its empirical co-production process, but concentrates the third phase almost entirely within the Pyramid Water Fountain artefacts rather than through an extended, iterative return to the practitioner community. Treating empirical and theoretical data as co-equal inputs aligns with the Mode 2 knowledge production from Gibbons et al. (1994), validating context-driven, application-oriented knowledge produced across academic and practitioner domains. The use of the ACD methodology constructs its artefacts through literature and empirical inputs by evaluating them retrospectively using a CFG rather than real-time organisational intervention. This positions the research as transdisciplinary, which trades the depth of real-time organisational embeddedness for broader, cross-context generalisability. According to the DSR contribution framework from (Gregor *et al.*, 2013:9), this research serves as an exaptation which extends known solutions (knowledge components) to new problems (SCA in developing countries).

5.3 Limitations

Several limitations bound the contribution. First, the framework is conceptual and interpretive: it structures and sequences knowledge but does not, in its present form, offer predictive capability, and the propositions above remain untested. Second, the PWTa's frequency-based filtering, while auditable, risks under-weighting low-frequency but theoretically significant constructs, notwithstanding the safeguards described in Section 3. Third, coding was led by a single researcher with consensus review rather than formal inter-coder reliability testing. Fourth, the empirical interview data derive from a single country; the findings are presented as transferable to comparable developing-

country settings rather than as universally generalisable. Finally, the sample size for the CFG was confined to a small sample size.

6. Conclusions, limitations and recommendations

6.1 Concluding remarks

This research aimed to develop a TD framework that integrates IE and ES knowledge to support a sustainable competitive advantage for developing countries. This is achieved by drawing on literature from global contexts and applying interview data from South Africa, a developing country used as a case study. The framework has not been validated in a real-world setting; therefore, all claims regarding practical applicability should be read as potential rather than demonstrated, pending the expert review, Delphi study or case application recommended in the conclusions. This intuitively responded to the research question crafted, seeking an appropriate method to integrate the fragmented IE and ES knowledge. The adapted ACD methodology employed strategic, lean and interpretivist systems thinking requirements that used morphological box intuition alongside visualisation techniques. Carrying out the methodology fulfilled the first objective to integrate IE and ES within TD contexts by creatively integrating the knowledge using PWTA. This informed the top-down design and side configurations across the business execution levels as part of the second objective articulated as the design component of this research.

A clear distinction must be drawn between what this study demonstrates and what it proposes. Demonstrated are the integration of IE and ES knowledge, the auditable PWTA filtering procedure and the resulting configuration of the pyramid waterfall framework. Proposed, and not yet demonstrated, are the framework's practical efficacy and its transferability beyond the South African interview context. Subject to this caveat, the work holds relevance for academics and practitioners alike. Given the TD nature of the framework, the theoretical and strategic aspects align with methodological and operationalised findings that produce empirical findings as an identified research gap declared earlier in this research. As for a practitioner, the application stream offers a strategy-to-implementation pathway that can be addressed with the multidimensional thinking the framework promotes.

6.2 Limitations and recommendations

Every source of research becomes a stepping stone for future work. More research could explore sector-specific renditions of this work since TD work is contentiously seen as too heterogeneous to various disentangled methodologies, as elucidated by Zierhofer and Burger (2007). Only by becoming more niche, can the framework become more intuitive and ease buy-in and implementation of sustainable competitive traits suggested by the integrated IE and ES knowledge.

TD validation is significantly more challenging than traditional disciplinary validation with knowledge merging at new intellectual links (Scholz & Steiner, 2015). Despite being grounded in literature and interview results, it has yet to be validated in real-world

contexts, as co-implementation was not a feature. It is for this reason that future research could explore ways of ensuring that real-world relevance and problem-solving ability are tested appropriately before full-scale implementation. Such mechanisms could entail the use of the Delphi technique, surveys or roadmap configurations amidst other research products. It is also argued that implementation science and TD validation remain underdeveloped (Moullin *et al.*, 2020), and therefore, further investigation could unlock new validation techniques within implementation science for increased stakeholder co-validation for one or more sectors.

Another aspect is that, although a hierarchical structure and guidance exist for the application streams within the framework, there is no incentivisation or quantitative analysis. This fosters opportunities for modelling the structure, attributes, sequencing and associations by means of structural equation modelling, simulation modelling or decision support system configurations to produce other research products within TD contexts.

Sołoducho-Pelc and Sulich (2020) created a taxonomy which defines SCA using six formal clusters. This TD framework merely aligns with many of the elements within four of the six clusters. However, leadership, shared value, market orientation and resource capabilities are not accounted for. It is therefore advised that further TD work invests intellect in unpacking these other SCA aspects. Another interesting research stream would be to explore industrial ecology, sustainability and environmental engineering knowledge so as to align knowledge for more diverse TD problem solving and a sustainable competitive advantage.

Ultimately, this research demonstrates how industrial engineering and environmental sustainability knowledge can be assembled to create a TD framework for competitiveness and relevance in developing countries.

Funding

This research did not receive any funding from the public, commercial or not-for-profit sectors.

CRedit authorship contribution statement

Author 1: Writing – original draft, formal analysis, data curation, conceptualisation, methodology, visualisations

Author 2: Writing – review & editing, conceptualisation

Declaration of conflicts of interest

There is no conflict of interest reported among the author(s).

References

- Al-Shaer, H., Albitar, K. & Hussainey, K. 2022. Creating sustainability reports that matter: an investigation of factors behind the narratives. *Journal of Applied Accounting Research*, 23(3):738-763.
- Alman, D. 2014. Using Systems Thinking to improve organisations. Available from: Date of access: October 2024. <https://www.calameo.com/read/001450934bd9804e0afe9>
- Apgar, J.M., Argumedo, A. & Allen, W. 2009. Building transdisciplinarity for managing complexity: Lessons from indigenous practice. *International Journal of Interdisciplinary Social Sciences*, 4(5):255-270.
- Axelsson, R. 2010. Integrative research and transdisciplinary knowledge production: A review of barriers and bridges. *Journal of Landscape Ecology*, 4(2):14-40.
- Bari, N., Chimhundu, R. & Chan, K.-C. 2022. Dynamic capabilities to achieve corporate sustainability: a roadmap to sustained competitive advantage. *Sustainability*, 14(3):1531.
- Barney, J. 1991. Firm resources and sustained competitive advantage. *Journal of Management*, 17(1):99-120. <https://doi.org/10.1177/014920639101700108>
- Bartels, N., Scherr, S.A., Gültekin, B., Ludborzs, S., Storck, S. & Zepp, A. 2024. Comic-Based Morphological Box: Enhancing Vision Design-A Research Preview. In. 2024 IEEE 32nd International Requirements Engineering Conference (RE). IEEE. pp. 330-336.
- Barton, J.R. & Gutiérrez-Antinopai, F. 2020. Towards a visual typology of sustainability and sustainable development. *Sustainability*, 12(19):7935.
- Benyus, J.M. 1997. *Biomimicry: Innovation inspired by nature*. Morrow New York.
- Bican, P.M. & Brem, A. 2020. Digital business model, digital transformation, digital entrepreneurship: Is there a sustainable "digital"? *Sustainability*, 12(13):5239.
- Bilge, P. 2017. Sustainable value creation by applying industrial engineering principles and methodologies.
- Biswas, W.K. & John, M. 2022. *Engineering for sustainable development: theory and practice*. John Wiley & Sons.
- Bracken, L.J., Bulkeley, H.A. & Whitman, G. 2015. Transdisciplinary research: understanding the stakeholder perspective. *Journal of environmental planning and management*, 58(7):1291-1308.
- Braun, V., Clarke, V., Boulton, E., Davey, L. & McEvoy, C. 2021. The online survey as a qualitative research tool. *International Journal of Social Research Methodology*, 24(6):641-654. <https://doi.org/10.1080/13645579.2020.1805550>
- Brough, A.R., Donnelly, G.E., Griskevicius, V., Markowitz, E.M., Raimi, K.T., Reeck, C., ... Wolske, K.S. 2020. Understanding how sustainability initiatives fail: A framework to aid design of effective interventions. *Social Marketing Quarterly*, 26(4):309-324.

- Brouwer, H., Woodhill, J., Hemmati, M., Verhoosel, K. & Van Vugt, S. 2019. The MSP guide: How to design and facilitate multi-stakeholder partnerships. Practical Action Publishing.
- Buetow, S. 2010. Thematic analysis and its reconceptualization as 'saliency analysis'. *Journal of health services research & policy*, 15(2):123-125.
- Caulfield, C. & Maj, S.P. 2001. A case for systems thinking and system dynamics. 2001 IEEE International Conference on Systems, Man and Cybernetics. e-Systems and e-Man for Cybernetics in Cyberspace (Cat.No.01CH37236), 5:2793-2798 vol.2795.
- Chan, R.Y., Lai, J.W. & Kim, N. 2022. Strategic motives and performance implications of proactive versus reactive environmental strategies in corporate sustainable development. *Business Strategy and the Environment*, 31(5):2127-2142.
- Cozzarin, B.P. & Percival, J.C. 2006. Complementarities between organisational strategies and innovation. *Economics of innovation and new technology*, 15(03):195-217.
- Craft, R.C. & Leake, C. 2002. The Pareto principle in organizational decision making. *Management Decision*, 40(8):729-733.
- Creswell, J.W. & Creswell, J.D. 2017. Research design: Qualitative, quantitative, and mixed methods approaches. Sage publications.
- D'Amato, D. & Korhonen, J. 2021. Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. *Ecological Economics*, 188:107143. <https://doi.org/10.1016/j.ecolecon.2021.107143>
- D'amato, D. & Korhonen, J. 2021. Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. *Ecological Economics*, 188:107143.
- Dalton, A., Wolff, K. & Bekker, B. 2021. Multidisciplinary Research as a Complex System. *International Journal of Qualitative Methods*, 20:16094069211038400. <https://journals.sagepub.com/doi/abs/10.1177/16094069211038400>
10.1177/16094069211038400
- Darwish, H. 2018. Expanding industrial thinking by formalizing the industrial engineering identity for the knowledge era. North-West University.
- Darwish, H. & Van Dyk, L. 2016. The industrial engineering identity: from historic skills to modern values, duties, and roles. *South African Journal of Industrial Engineering*, 27(3):50-63.
- Du Preez, N. & Louw, L. 2007. Managing the knowledge supply chain to support innovation. In. *Proceedings: International Conference on Competitive Manufacturing*. pp. 65-78.
- Eijdenberg, E.L., Sabokwigina, D. & Masurel, E. 2019. Performance and environmental sustainability orientations in the informal economy of a least developed country. *International Journal of Entrepreneurial Behavior & Research*, 25(1):129-149.
- Emas, R. 2015. The concept of sustainable development: definition and defining principles. *Brief for GSDR*, 2015(10):13140-13143.

- Evans, S., Vladimirova, D., Holgado, M., Van Fossen, K., Yang, M., Silva, E.A. & Barlow, C.Y. 2017. Business model innovation for sustainability: Towards a unified perspective for creation of sustainable business models. *Business strategy and the environment*, 26(5):597-608.
- Fatima, M., Ata, G. & Rizwan, A. 2023. Institutional pressures and sustainable business practices: A case of strategic environmental management. *Global Economics Review*, 8(1):196-212.
- Finch, N. 2005. The motivations for adopting sustainability disclosure.
- Francis, J.J., Johnston, M., Robertson, C., Glidewell, L., Entwistle, V., Eccles, M.P. & Grimshaw, J.M. 2010. What is an adequate sample size? Operationalising data saturation for theory-based interview studies. *Psychology & Health*, 25(10):1229-1245.
<https://doi.org/10.1080/08870440903194015> 10.1080/08870440903194015
- Game, E.T., Meijaard, E., Sheil, D. & McDonald-Madden, E. 2014. Conservation in a wicked complex world; challenges and solutions. *Conservation Letters*, 7(3):271-277.
- Garud, R., Tuertscher, P. & Van de Ven, A.H. 2013. Perspectives on innovation processes. *Academy of Management Annals*, 7(1):775-819.
- Geissdoerfer, M., Savaget, P., Bocken, N.M. & Hultink, E.J. 2017. The Circular Economy—A new sustainability paradigm? *Journal of cleaner production*, 143:757-768.
- Genç, E. & Benedetto, C.A.D. 2019. A comparison of proactive and reactive environmental strategies in green product innovation. *International Journal of Innovation and Sustainable Development*, 13(3-4):431-451.
- Gibbons, M., Limoges, C., Scott, P., Schwartzman, S. & Nowotny, H. 1994. The new production of knowledge: The dynamics of science and research in contemporary societies.
- Githui, F. & Njuru, J. 2026. The Strategic Impact of Circular Economy Implementation on Competitive Advantage and Financial Resilience in Select Emerging Market Industries.
- Goodland, R.J., Daly, H.E. & El Serafy, S. 1993. The urgent need for rapid transition to global environmental sustainability. *Environmental conservation*, 20(4):297-309.
- Gregor, S.D., Müller, O. & Seidel, S. 2013. Reflection, Abstraction And Theorizing In Design And Development Research. In. *European Conference on Information Systems*.
- Grosfeld-Nir, A., Ronen, B. & Kozlovsky, N. 2007. The Pareto managerial principle: when does it apply? *International Journal of Production Research*, 45(10):2317-2325.
<https://doi.org/10.1080/00207540600818203>
- Gupta, N. & Benson, C.C. 2011. Sustainability and competitive advantage: An empirical study of value creation. In. *Competition forum*.
- Gutierrez, E., Sandstrom, G.O., Janhager, J. & Ritzen, S. 2008. Innovation and decision making: understanding selection and prioritization of development projects. In. 2008 4th IEEE International Conference on Management of Innovation and Technology. IEEE. pp. 333-338.

Hadorn, G.H., Hoffmann-Riem, H., Biber-Klemm, S., Grossenbacher-Mansuy, W., Joye, D., Pohl, C., ... Zemp, E. 2008. Handbook of transdisciplinary research. 10. Springer.

Hart, S.L. & Milstein, M.B. 2003. Creating sustainable value. *Academy of Management Perspectives*, 17(2):56-67.

Hart, S.L. & Christensen, C.M. 2002. The great leap: Driving innovation from the base of the pyramid. *MIT Sloan management review*, 44(1):51.

Heeks, R. 2006. Using competitive advantage theory to analyze IT sectors in developing countries: a software industry case analysis. *Information Technologies & International Development*, 3(3):pp. 5-34.

Hermundsdottir, F. & Aspelund, A. 2021. Sustainability innovations and firm competitiveness: A review. *Journal of Cleaner Production*, 280:124715.
<https://doi.org/10.1016/j.jclepro.2020.124715>

Hermundsdottir, F. & Aspelund, A. 2021. Sustainability innovations and firm competitiveness: A review. *Journal of Cleaner Production*, 280:124715.
<https://www.sciencedirect.com/science/article/pii/S0959652620347594>
<https://doi.org/10.1016/j.jclepro.2020.124715>

Hoover, S.P., Rinderle, J.R. & Finger, S. 1991. Models and abstractions in design. *Design Studies*, 12:237-245.

(IISE), I.o.I.a.S.E. 2021. IISE Body of Knowledge.
<https://www.iise.org/Details.aspx?id=43631>

Javed, H., Du, J. & Farooq Islam, M. 2025. Unpacking organizational capabilities and green Innovation for sustainable Performance: The role of environmental regulations in manufacturing industry. *Journal of Cleaner Production*, 507:145453.
<https://doi.org/10.1016/j.jclepro.2025.145453>

Jenkins, B. 2002. Organisation for sustainability. *Australian Journal of Environmental Management*, 9(4):243-251.

Jesiek, B.K., Buswell, N.T. & Mazzurco, A. 2016. Becoming boundary spanning engineers: Research methods and preliminary findings. In. 2016 ASEE Annual Conference & Exposition.

Jørgensen, S.E. 2016. Urgent needs for multidisciplinary and transdisciplinary research. *Energy, Ecology and Environment*, 1(1):3-9.

Jovanovic, V. 2013. Multidisciplinary design and modern manufacturing as driving forces for industrial engineers of the future. *Chap*, 60:969-984.

Juran, J.M. 2003. *Juran on leadership for quality*. Simon and Schuster.

Kahn, K.B. 2018. Understanding innovation. *Business Horizons*, 61(3):453-460.
<https://doi.org/10.1016/j.bushor.2018.01.011>

Kapsali, V. 2022. Sustainable approaches to textile design: Lessons from biology. *Proceedings of DRS*,

- Kirchherr, J., Reike, D. & Hekkert, M. 2017. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127:221-232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- Klein, J.T. 2001. *Transdisciplinarity: Joint problem solving among science, technology, and society: An effective way for managing complexity*. Springer Science & Business Media.
- Klein, J.T. 2008. Evaluation of interdisciplinary and transdisciplinary research: a literature review. *American journal of preventive medicine*, 35(2):S116-S123.
- Kuratko, D.F., Covin, J.G. & Hornsby, J.S. 2014. Why implementing corporate innovation is so difficult. *Business Horizons*, 57(5):647-655.
- Lang, D.J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., ... Thomas, C.J. 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science*, 7:25-43.
- Leese, J., Li, L.C., Nimmon, L., Townsend, A.F. & Backman, C. 2021. Moving beyond "until saturation was reached": Critically examining how saturation is used and reported in qualitative research.
- Li, B., Duan, Z. & Tu, Q. 2025. Balancing financial performance and sustainability: Examining the influence of CEO busyness on firm performance and ESG intensity. *Journal of Cleaner Production*, 525:146581. <https://doi.org/10.1016/j.jclepro.2025.146581>
- Lister, G. & Donaldson, K. 2004. New roles for industrial engineers in developing countries. *South African Journal of Industrial Engineering*, 15(1):43-52.
- Liu, X., Derudder, B., Csomós, G. & Taylor, P. 2013. Featured graphic. Mapping shifting hierarchical and regional tendencies in an urban network through alluvial diagrams. *Environment and Planning A*, 45(5):1005-1007.
- Loorbach, D., Frantzeskaki, N. & Avelino, F. 2017. Sustainability transitions research: transforming science and practice for societal change. *Annual review of environment and resources*, 42:599-626.
- Lozano, R. 2008. Envisioning sustainability three-dimensionally. *Journal of cleaner production*, 16(17):1838-1846.
- MacArthur, E. 2013. Towards the circular economy. *Journal of industrial ecology*, 2(1):23-44.
- Madu, C.N. 1999. A Decision Support Framework for Environmental Planning in Developing Countries. *Journal of Environmental Planning and Management*, 42:287-313.
- Mak, J.W. 2014. Conducting research that is both ethical and responsive to the health needs of a developing country. *International e-Journal of Science, Medicine and Education*:19-23.
- Malterud, K. 2012. Systematic text condensation: a strategy for qualitative analysis. *Scand J Public Health*, 40(8):795-805. [10.1177/1403494812465030](https://doi.org/10.1177/1403494812465030)
- Mangaroo-Pillay, M. & Roopa, M. 2021. Beyond the industrial engineering frontier: A few steps in history and a giant leap into the future. *South African Journal of Industrial Engineering*, 32(3):1-9.

- Mangaroo-Pillay, M., Coetzee, R.J.J.o.I.E. & Management. 2022. Lean frameworks: A systematic literature review (SLR) investigating methods and design elements. 15(2):202-214.
- Markley, M.J. & Davis, L. 2007. Exploring future competitive advantage through sustainable supply chains. *International Journal of Physical Distribution & Logistics Management*, 37(9):763-774.
- Mazza, R. & Berre, A. 2007. Focus group methodology for evaluating information visualization techniques and tools. In. 2007 11th International Conference Information Visualization (IV'07). IEEE. pp. 74-80.
- McDonald, N., Schoenebeck, S. & Forte, A. 2019. Reliability and Inter-rater Reliability in Qualitative Research: Norms and Guidelines for CSCW and HCI Practice. *Proc. ACM Hum.-Comput. Interact.*, 3(CSCW): Article 72. <https://doi.org/10.1145/3359174> 10.1145/3359174
- Mensah, J. 2019. Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. *Cogent social sciences*, 5(1):1653531.
- Monat, J.P. & Gannon, T.F. 2015. What is Systems Thinking? A Review of Selected Literature Plus Recommendations. In.
- Monica Chiarini, T., Hevner, A.R. & Berndt, D.J. 2010. Focus Groups for Artifact Refinement and Evaluation in Design Research. *Communications of the Association for Information Systems*, 26:27. <https://doi.org/10.17705/1CAIS.02627>
- Morelli, J. 2011. Environmental sustainability: A definition for environmental professionals. *Journal of environmental sustainability*, 1(1):2.
- Morgan, D. 1993. Focus groups and surveys. In. *Annual Meeting of the America Sociology Association*. Pittsburg, PA.
- Morgan, D.L. 1996. Focus groups as qualitative research. 16. Sage publications.
- Morse, J.M., Barrett, M., Mayan, M., Olson, K. & Spiers, J. 2002. Verification strategies for establishing reliability and validity in qualitative research. *International journal of qualitative methods*, 1(2):13-22.
- Moullin, J.C., Dickson, K.S., Stadnick, N.A., Albers, B., Nilsen, P., Broder-Fingert, S., ... Aarons, G.A. 2020. Ten recommendations for using implementation frameworks in research and practice. *Implementation science communications*, 1(1):42.
- Nicolescu, B. 2002. Manifesto of transdisciplinarity. suny Press.
- Nonaka, I. & Takeuchi, H. 1995. The knowledge-creating company: How Japanese companies create the dynamics of innovation. Oxford university press.
- Northcutt, N. & McCoy, D. 2004. Interactive qualitative analysis: A systems method for qualitative research. Sage.
- O'Connor, C. & Joffe, H. 2020. Intercoder reliability in qualitative research: Debates and practical guidelines. *International Journal of Qualitative Methods*, 19:1609406919899220. <https://doi.org/10.1177/1609406919899220>

O'Raghallaigh, P., Sammon, D. & Murphy, C. 2012. Using focus groups to evaluate artefacts in design research. In. The 6th European Conference on Information Management and Evaluation University College Cork. pp. 251-257.

Oduro, S. & Haylemariam, L.G. 2025. Effect of social and environmental sustainability on SME competitiveness: a meta-analytic review. *Management Review Quarterly*:1-32.

Osobajo, O.A., Oke, A., Lawani, A., Omotayo, T.S., Ndubuka-McCallum, N. & Obi, L. 2022. Providing a roadmap for future research agenda: A bibliometric literature review of sustainability performance reporting (SPR). *Sustainability*, 14(14):8523.

Parnaby, J. 2014. Designing effective organizations. *International Journal of Technology Management*,

Perrott, B. 2014. The sustainable organisation: Blueprint for an integrated model. *Journal of Business Strategy*, 35(3):26-37.

Pimm, S.L., Alibhai, S., Bergl, R., Dehgan, A., Giri, C., Jewell, Z., ... Loarie, S. 2015. Emerging technologies to conserve biodiversity. *Trends in ecology & evolution*, 30(11):685-696.

Pisano, G.P. 2015. You need an innovation strategy. *Harvard business review*, 93(6):44-54.

Poliandri, D., Perazzolo, M., Pillera, G.C. & Giampietro, L. 2023. Dematerialized participation challenges: Methods and practices for online focus groups. *Frontiers in Sociology*, 8:1145264.

Rahimifard, S. & Clegg, A.J. 2008. The role of the engineering community in sustainable development. *International Journal of Sustainable Engineering*, 1(1):1-2.

Rattalino, F. 2019. Sustainability and competitive advantage: a case of patagonia's sustainability-driven innovation and shared value. In. *Social Entrepreneurship: Concepts, Methodologies, Tools, and Applications*: IGI Global Scientific Publishing. pp. 1549-1574.

Raworth, K. 2017. *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Chelsea Green Publishing.

Redclift, M. 2002. *Sustainable development: Exploring the contradictions*. Routledge.

Rodriguez, M.A., Ricart, J.E. & Sanchez, P. 2002. Sustainable development and the sustainability of competitive advantage: A dynamic and sustainable view of the firm. *Creativity and innovation management*, 11(3):135-146.

Roopa, M. 2021. Designing a Lean and Green framework for the reduction of GHG emissions in the South African manufacturing industry. North-West University (South Africa).

Roopa, M. 2024. An Industrial Engineering Lighthouse Model for Transdisciplinary Problem Solving and Sustainable Development in South Africa. Paper presented at the SAIIE 34 - Illuminate, Riverside Sun, Vanderbijlpark, South Africa.

Roopa, M. & Siriram, R. 2026. Identifying harmony between industrial engineering and environmental sustainability in South Africa. *Sustainable Futures*, 11:101695.

<https://www.sciencedirect.com/science/article/pii/S2666188826000535>
<https://doi.org/10.1016/j.sfr.2026.101695>

Roopa, M., Siriram, R. & Coetzee, R. 2024. Exploring Industrial Engineering Knowledge and Environmental Sustainability. *Sustainability*, 16(17):7392. <https://www.mdpi.com/2071-1050/16/17/7392>

Ross, J.W., Weill, P. & Robertson, D. 2006. *Enterprise architecture as strategy: Creating a foundation for business execution*. Harvard business press.

Rotondo, F., Fadda, N., Ezza, A. & Giovanelli, L. 2025. The impact of sustainability orientation on performance in higher education. An empirical longitudinal investigation. *Journal of Cleaner Production*, 504:145429.
<https://www.sciencedirect.com/science/article/pii/S0959652625007796>
<https://doi.org/10.1016/j.jclepro.2025.145429>

Salvendy, G. 2001. *Handbook of industrial engineering: technology and operations management*. John Wiley & Sons.

Sandelowski, M., Voils, C.I. & Knafl, G. 2009. On quantitizing. *Journal of Mixed Methods Research*, 3(3):208-222. <https://doi.org/10.1177/1558689809334210>

Sapsanguanboon, W., Faijaidee, W. & Potasin, L. 2025. Strategic integration of sustainability for competitive advantage: A framework for balancing the triple bottom line. *Corp. Gov. Sustain. Rev.*, 9:110-119.

Sari, Y., Hidayatno, A., Suzianti, A., Hartono, M. & Susanto, H. 2021. A corporate sustainability maturity model for readiness assessment: a three-step development strategy. *International Journal of Productivity and Performance Management*, 70(5):1162-1186.

Schmidt, F.L. & Hunter, J.E. 1978. MODERATOR RESEARCH AND THE LAW OF SMALL NUMBERS 1. *Personnel Psychology*, 31(2):215-232.

Schneider, J.M. 2000. Focus Groups for Libraries and Librarians. *Bulletin of the Medical Library Association*, 88(3):280.

Scholz, R.W. & Steiner, G. 2015. The real type and ideal type of transdisciplinary processes: part II—what constraints and obstacles do we meet in practice? *Sustainability Science*, 10(4):653-671.

Schultze, U. & Avital, M. 2011. Designing interviews to generate rich data for information systems research. *Information and organization*, 21(1):1-16.

Schwarz, R.M. 1994. *The Skilled Facilitator: Practical Wisdom for Developing Effective Groups*. A Joint Publication in the Jossey-Bass Management, Public Administration, and Nonprofit Sector Series. ERIC.

Seidel, S., Recker, J. & Vom Brocke, J. 2013. Sensemaking and sustainable practicing: Functional affordances of information systems in green transformations. *MIS quarterly*:1275-1299.

Sharkie, R. 2003. Knowledge creation and its place in the development of sustainable competitive advantage. *Journal of Knowledge management*, 7(1):20-31.

- Sharma, R. & Gupta, H. 2024. Harmonizing sustainability in industry 5.0 era: Transformative strategies for cleaner production and sustainable competitive advantage. *Journal of Cleaner Production*, 445:141118.
- Siriram, R. 2011. Convergence of technologies. *South African Journal of Industrial Engineering*, 22(1):13-27.
- Skjølsvik, T. 2020. Understanding the strategy-innovation link in an era of disruptions. *Technology Innovation Management Review*,
- Sołoducho-Pelc, L. & Sulich, A. 2020. Between sustainable and temporary competitive advantages in the unstable business environment. *Sustainability*, 12(21):8832.
- Srivastava, M., Franklin, A. & Martinette, L. 2013. Building a sustainable competitive advantage. *Journal of technology management & innovation*, 8(2):47-60.
- Stasko, J., Catrambone, R., Guzdial, M. & McDonald, K. 2000. An evaluation of space-filling information visualizations for depicting hierarchical structures. *International journal of human-computer studies*, 53(5):663-694.
- Stewart, I. & Fenn, P. 2006. Strategy: the motivation for innovation. *Construction innovation*, 6(3):173-185.
- Stubbs, W. & Cocklin, C. 2008. Conceptualizing a "sustainability business model". *Organization & environment*, 21(2):103-127.
- Tang, K.C. & Davis, A. 1995. Critical factors in the determination of focus group size. *Family practice*, 12 4:474-475.
- Teece, D.J. 2007. Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. *Strategic Management Journal*, 28(13):1319-1350. <https://doi.org/10.1002/smj.640>
- Tiwari, P., Sadeghi, J.K. & Eseonu, C. 2020. A sustainable lean production framework with a case implementation: Practice-based view theory. *Journal of Cleaner Production*, 277:123078.
- Toman, M.A. 1992. The difficulty in defining sustainability.
- Tsoku, T., van Dyk, L. & Maisiri, W. 2024. The role of industrial engineering and its impact on sustainability: a systematic review approach. *South African Journal of Industrial Engineering*, 35(3):70-79.
- Van de Ven, A.H. 1986. Central problems in the management of innovation. *Management science*, 32(5):590-607.
- van der Hel, S. 2016. New science for global sustainability? The institutionalisation of knowledge co-production in Future Earth. *Environmental science & policy*, 61:165-175.
- van der Linde, N. & Roopa, M. 2021. Designing a decision support system for workforce planning in a South African tertiary institution.

Wang, N., Zhang, S.J. & Wang, W. 2022. Impact of environmental innovation strategy on green competitiveness: Evidence from China. *International journal of environmental research and public health*, 19(10):5879.

Waqas, M., Honggang, X., Ahmad, N., Khan, S.A.R. & Iqbal, M. 2021. Big data analytics as a roadmap towards green innovation, competitive advantage and environmental performance. *Journal of Cleaner Production*, 323:128998. <https://doi.org/10.1016/j.jclepro.2021.128998>

Whittemore, R., Chase, S.K. & Mandle, C.L. 2001. Validity in qualitative research. *Qualitative health research*, 11(4):522-537.

Wibeck, V., Eliasson, K. & Neset, T.-S. 2022. Co-creation research for transformative times: Facilitating foresight capacity in view of global sustainability challenges. *Environmental Science & Policy*, 128:290-298.

Willis, K.J. & Petrokofsky, G. 2017. The natural capital of city trees. *Science*, 356(6336):374-376.

Wisniak, J. 2004. The nature and composition of water.

Ziaul, I.M. & Shuwei, W. 2023. Environmental sustainability: A major component of sustainable development. *International Journal of Environmental, Sustainability, and Social Science*, 4(3):900-907.

Zierhofer, W. & Burger, P. 2007. Disentangling transdisciplinarity: an analysis of knowledge integration in problem-oriented research. *Science & Technology Studies*, 20(1):51-72.

Zokaei, K., Lovins, H., Wood, A. & Hines, P. 2013. Creating a lean and green business system: techniques for improving profits and sustainability. CRC press.

Chapter 8

Analysis of SLR and Interviews

8 Analysis of SLR and Interviews

8.1 Introduction

Although the preceding chapters contain results obtained at distinct stages in the research, an opportunity exists to further reflect on these results and findings. This chapter tries to further critique results from the SLR and interviews.

8.2 SLR

A simple yet effective means of understanding the nature of a body of literature is to make use of word clouds. Using the titles from the 24 papers, a word cloud was generated and is presented in Figure 24.



Figure 24 Title word cloud of 24 papers from SLR

An anticipated finding is that ‘sustainable’ and ‘sustainability’ are the two largest terms in the word cloud, given the search protocol keyword requirements, but the more diagnostically useful signal lies in the relative sizing of the second tier of terms. ‘Industry’ and ‘industrial’ both outsize ‘engineering’ in the visualisation, while explicitly IE-branded language, such as ‘methodology’, ‘systems’ and ‘process’, is present but visually subordinate. This asymmetry suggests that the papers retrieved by the SLR are authored predominantly from an applied, sector-facing standpoint rather than from a position that foregrounds industrial engineering as a named contributing discipline. This is consistent with the broader disciplinary invisibility of industrial engineering identified elsewhere in this research, where the profession’s contributions are frequently absorbed into generic industrial or organisational narratives rather than attributed to industrial engineering as a distinct body of knowledge (Darwish & van Dyk, 2016). Read alongside the near-absence of explicit Industry 4.0 or Industry 5.0 terminology in the same corpus, the word cloud offers early visual corroboration, before any thematic coding, of the central lack of formalisation this study sets out to address. It becomes evident that the contribution of industrial to environmental sustainability outcomes is present in the literature but is rarely labelled as such.

One way of trying to study the rate of interest in research papers is by visualising the cumulative years of the research papers. Figure 25 demonstrates this rise in research papers relative to each year using the SLR databases declared in Chapter 4.

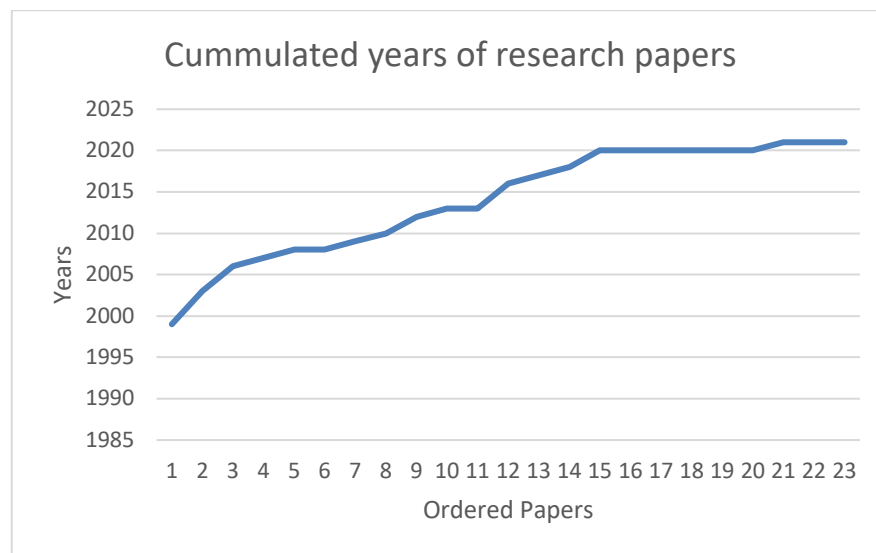


Figure 25 Cumulative years of SLR search results

As can be deduced from the cumulated years of research papers, there was a steady increase with a sudden increase in research papers in 2020 and 2021. This sudden increase in research indicates the growing focus on environmental sustainability. 2020 showcases the largest body of literature used in the particular stage of this research. The sudden acceleration visible from 2020 onward warrants closer interrogation than a simple observation. The timing coincides with at least three plausible external drivers operating simultaneously: the mainstreaming of Environmental, Social and Governance (ESG) reporting obligations among listed companies, the post-2015 diffusion of the UN Sustainable Development Goals into academic research agendas, and the disruption of global supply chains during the COVID-19 pandemic. These are documented elsewhere in this research as a period of heightened environmental awareness (Severo et al., 2021). Another observation that the cumulative curve cannot determine is whether this represents a durable shift in scholarly attention toward the intersection of industrial engineering and environmental sustainability, or a short-lived reactive spike tied to this specific historical moment. Given that the SLR search protocol imposed no lower time bound, the near-flat trajectory before 2017 suggests that structured academic interest in this specific intersection is a comparatively recent phenomenon. still in an early, formative stage rather than a mature research area. This has a direct bearing on the novelty claimed elsewhere in this research, namely the scarcity of literature before 2017, combined with the sudden late-stage acceleration. This indicates that this study is intervening in a field that is still actively defining its own boundaries and terminology.

When combining the results from Figures 24 and 25, the sustainability narrative is evident in the research, with growing efforts to solve challenges in this domain. Another method to chart the data is to associate the affiliation of research globally. Figure 28 provides the geographical charting of the SLR data.

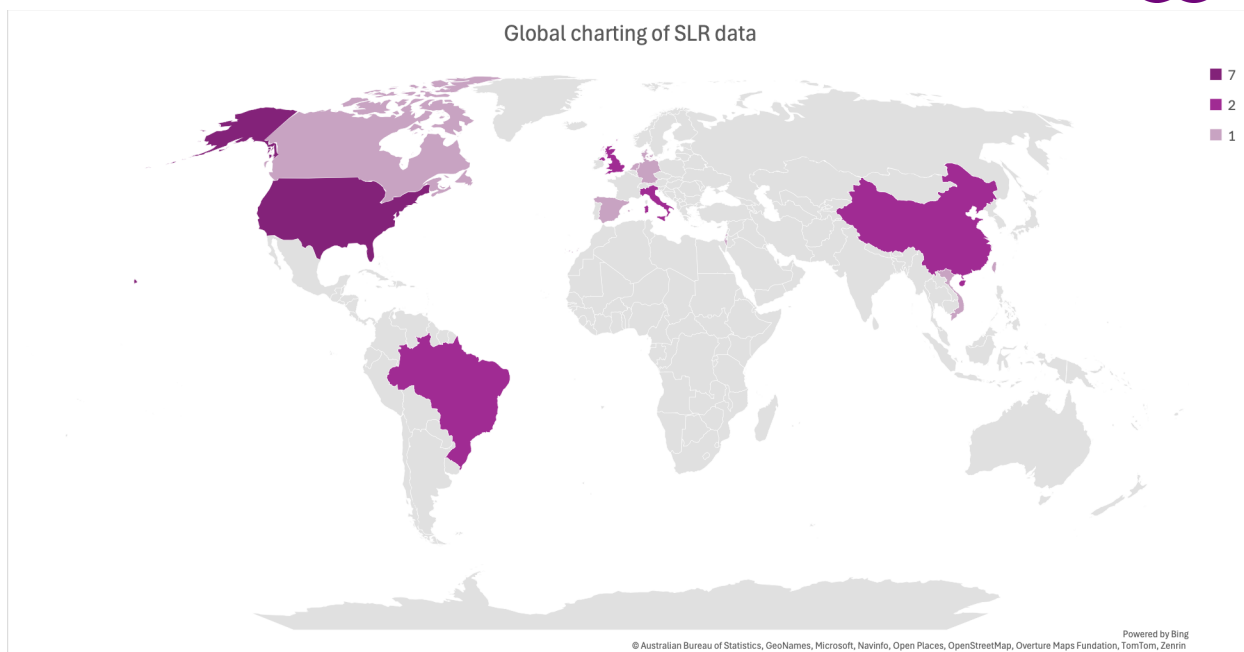


Figure 26 Geographical charting of SLR data

As evidenced by the geographical representation, the majority of research stems from East Asia and the Americas. When revisiting Table 1 from Chapter 1, the same Scimago rankings are represented, given with the charting of USA, China and the likes of other countries from the top 8. The complete absence of African-based research within the papers is arguably the single most consequential finding to emerge from the geographic charting exercise. This is not merely a descriptive gap. The concentration of research output in East Asia, North America, Western Europe and Brazil mirrors well-documented asymmetries in global research infrastructure and funding, and the resulting scholarship is disproportionately shaped by industrial, regulatory and energy contexts that differ substantially from those found in South Africa and other developing economies (Blicharska et al., 2017). This is significant methodologically and substantively since strategies, theories, methods and practices are synthesised from a literature base concentrated in developed and East Asian economies and cannot be assumed to transfer into a South African industrial and regulatory context without further contextualisation. This finding therefore does more than describe a gap in the literature; it substantiates the geographic novelty claimed for this research programme, and it foreshadows why the subsequent interview phase, conducted exclusively with South African industrial engineers and environmental practitioners, was a methodologically necessary complement to the SLR rather than a redundant second data source.

8.3 Interviews

The interviews made use of snowball purposive sampling until saturation was reached. This process led to 24 participants being interviewed. The population sampled was industrial engineers or environmental managers/practitioners working in South Africa. The results from the interviews are argued to help produce transdisciplinary knowledge. This is warranted by the inclusion of academics and non-academics (practitioners) which represent a vast array of industries across South Africa. The interview population industry representation has been showcased in Figure 29. The industry classification was used to dissect appropriate representation given specialised knowledge required in each field.

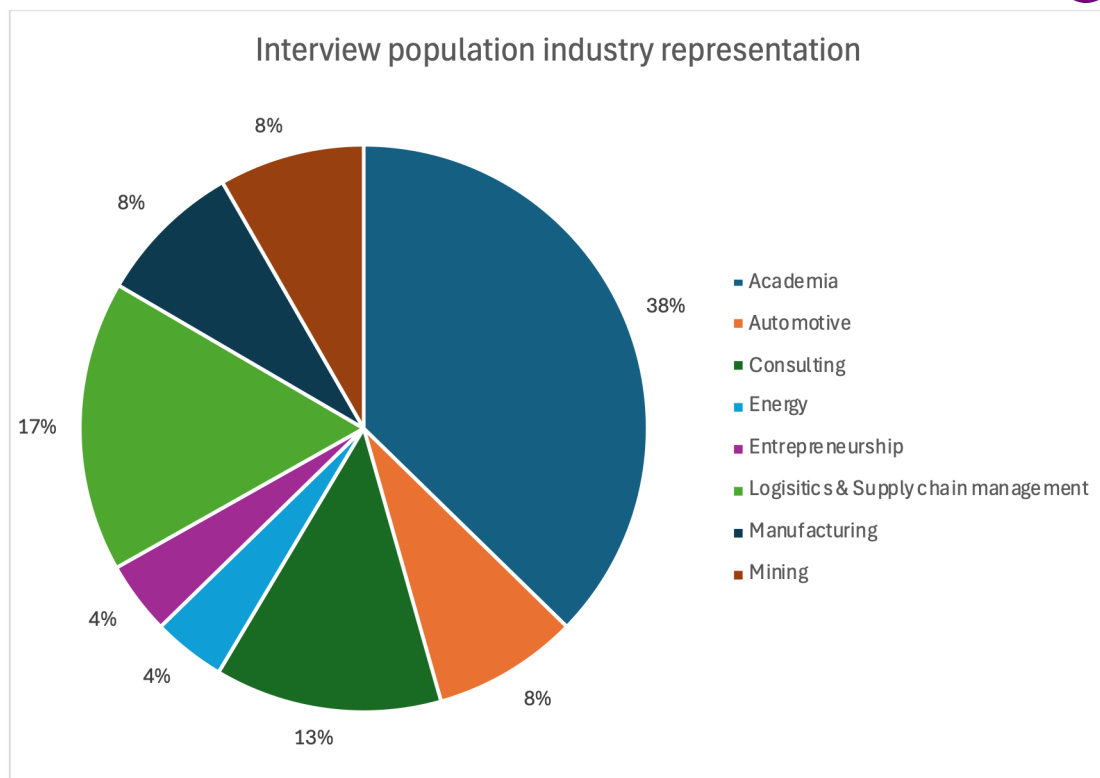


Figure 27 Industry representation of interview sample

Cross-referencing the industry representation figures against the per-participant knowledge component contributions recorded during the interview phase reveals a pattern not otherwise visible in the aggregate percentages alone. Academia, the most heavily represented category at 38 per cent of the sample, was also disproportionately associated with theoretically dense contributions spanning management theory, systems theory and industrial ecology, while participants drawn from operationally embedded sectors such as manufacturing, energy and logistics contributed a comparatively higher share of concrete methods and practices. Such methods and practices included aspects such as value stream mapping, root cause analysis and standard operating procedures. This distribution is a double-edged methodological outcome. On one hand, it strengthens the transdisciplinary credibility of the sample by ensuring that both theoretical and operational voices are represented in roughly the proportions one would expect from a purposive, snowballing sample seeded through academic and professional networks. On the other hand, the comparatively low representation of the energy sector and entrepreneurship was a notable limitation given the centrality of energy security and loadshedding to the South African sustainability discourse referenced elsewhere in the interview findings alongside job creation opportunities. A more energy-sector-weighted sample may have surfaced additional operational knowledge components specific to grid-constrained environments that the current sample was underpowered to detect.

Another perspective on the interview results is to consider the thematic analysis performed in atlas.ti, alongside the interaction between the codes. Figure 30 boasts the overlap between the coded text clustered within the respective codes.

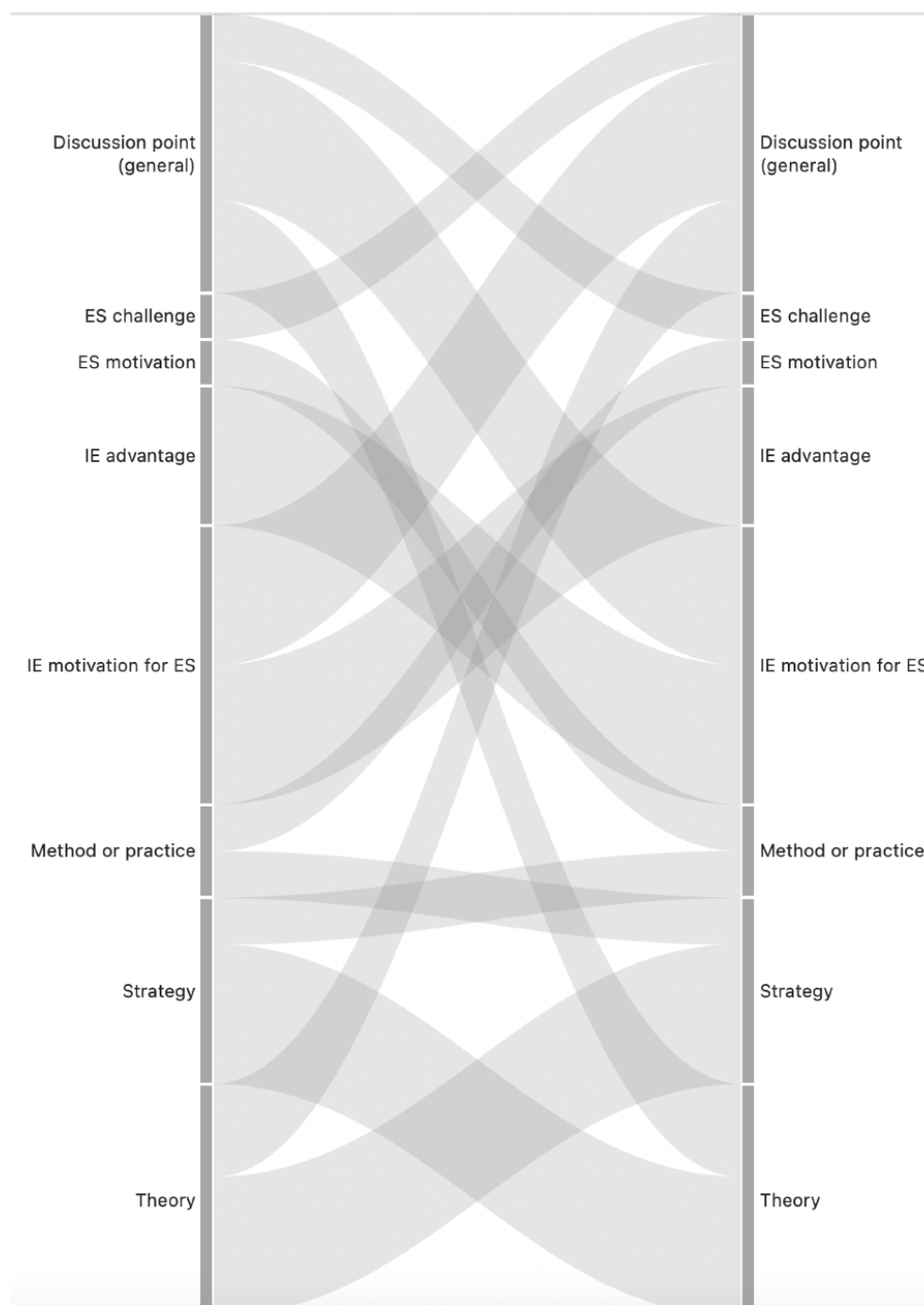


Figure 28 Sankey diagram of interview codes interaction

The IE motivation for environmental sustainability has the most overlap with the other codes and is the most intertwined. Ironically, the most siloed interaction is between the motivation and challenges of environmental sustainability with methods and general discussion points.

The pattern visible in the Sankey diagram, dense overlap around 'IE motivation for ES' contrasted with the comparative isolation of methods, practices and general discussion points, is best interpreted through the lens of the knowledge-to-action or 'know-do' gap that has been extensively documented in implementation science. Participants converge readily on why industrial engineering should engage with environmental sustainability; conviction, motivation and perceived advantage are widely shared and richly

interconnected codes. The same convergence does not extend to how that conviction should be operationalised. Methods and practices, along with general discussion points, remain comparatively siloed from the motivational codes, indicating that consensus on the value of IE-ES integration has not yet translated into a shared operational vocabulary for achieving it. This distinction carries direct implications for artefact design as an intervention that merely reinforces motivation and communicates why IE and ES should be integrated. The more productive design target, based on this Sankey pattern, is the poorly connected methods and practices space, since this is where the actual translation from conviction into operational routine appears to break down.

During the artefact design, PWTa was applied. Here, the life cycle assessment and analysis and its abbreviation LCA, were duplicated and therefore condensed into one code with a frequency of 12. All of these were naturally isolated since they share no association with the traditional IE taxonomy model and are a deficiency when trying to create transdisciplinary knowledge that uses IE and ES. Some of these were later filtered out of the analysis. These concepts and their classification are stipulated in Table 13.

Table 13 Knowledge components filtered out of PWTa and TD artefact creation

IE or ES	Knowledge component	Concept(s)
ES	Strategy	Circular economy and sharing principles, scientific knowledge creation, environmental protection and management, planetary boundary, eco-effective symbiosis and industrial parks
IE	Theory	Value engineering and creation, and green engineering
ES	Theory	Environmental sustainability theory: Sustainable development and sustainability models, ecological engineering and modernisation theory, environmental reform, industrial ecosystems and eco-industrial systems, circular humansphere and industrial ecology.

The knowledge components filtered out of the PWTa process merit closer scrutiny than their exclusion from the final TD artefact might suggest. Several of the discarded ES strategy components, circular economy and sharing principles, eco-effective symbiosis, eco-industrial parks, and the discarded ES theory components, industrial ecosystems, eco-industrial systems and industrial ecology itself, do not represent weak or peripheral ideas. They collectively describe one of the most established transdisciplinary research traditions concerned with exactly the systems-level integration this study pursues (Frosch & Gallopoulos, 1989; Chertow, 2000; Ehrenfeld, 2004). Their exclusion from the artefact was therefore a deliberate scoping decision driven by low code density and poor alignment with the IISE taxonomy model used to structure the artefact, rather than evidence that these concepts lack relevance to the IE-ES relationship. This distinction matters for how the resulting TD artefact should be interpreted: it is best understood as one operationalisation of the IE-ES relationship compatible with the practitioner-oriented, taxonomy-aligned scope adopted in this research, rather than an exhaustive account of

every theoretical resource available for integrating industrial engineering and environmental sustainability. Industrial ecology, in particular, remains an available and complementary body of theory that future artefact iterations could draw on directly, rather than filtering out, especially where systems-level, cross-organisational flows are the focus rather than firm-level practice.

8.4 Chapter summary

This chapter provides an analysis and synthesis of the results derived from the Systematic Literature Review (SLR) and the primary interview phase, bridging the gap between theoretical trends and practitioner reality. Through a word cloud analysis of the SLR, it becomes evident that while sustainability and environmental concerns dominate the literature, the research is largely applied within industrial contexts rather than being prescriptive to the engineering discipline itself. This global body of work saw a significant spike in 2020 and 2021, yet geographical charting reveals a stark deficiency in African-based research. Complementing these findings, the interview process reached saturation with 24 South African participants, creating a melting pot of transdisciplinary knowledge across academia, logistics, and consulting. Thematic analysis via Sankey diagrams highlights that while the motivation for Industrial Engineering (IE) to adopt environmental sustainability (ES) is deeply intertwined with other factors, the practical methods and challenges often remain ironically siloed. The next chapter incorporates a Use Case Analysis (UCA) that was used to test the integration of the knowledge components but also validate the IE pyramid waterfall model produced in this research.

Chapter 9

9 Use Case Analysis (UCA)

This chapter serves as a conference paper **accepted and presented** the 32nd *Conference on Engineering, Technology and Innovation in Porto, June 2026*. Confirmation of acceptance has been provided in Appendix E.

Title: A multi-use case analysis for a sustainable competitive advantage using industrial engineering and environmental sustainability knowledge

Abstract: Transdisciplinary knowledge has demonstrated societal and environmental gains. This research explores the notion of a sustainable competitive advantage (SCA) by performing a use case analysis (UCA). The UCA is used to evaluate an integrated knowledge between industrial engineering (IE) and environmental sustainability (ES). This integrated knowledge recommends mechanisms for South Africa, and in this research, generalised for other countries. These components are specific strategies, theories, and methods and practices associated with the three business execution levels. The UCA primarily aligns features of the framework with international and South African literature, with conformance mapped against the knowledge components, Sustainable Development Goals, VRIO framework and three stages of Dynamic Capabilities. These demonstrate that the integration of IE and ES can best advance sustainable competitive advantages for South Africa and the likes of many other developing countries.

Keywords: Industrial Engineering; Environmental Sustainability; Sustainable Competitive Advantage; Use Case Analysis; Sustainable Development Goals; African Union 2063 Goals

Introduction: Chapter 9 reproduces a conference paper accepted for the 32nd Conference on Engineering, Technology and Innovation in Porto, and represents the validation-oriented chapter, shifting the research programme's centre of gravity from artefact construction (Chapters 6 and 7) toward artefact testing. The chapter opens by restating IE's multidisciplinary, value-balancing character and environmental sustainability's persistent neglect relative to more immediate economic and energy concerns, before directly citing Chapter 4 (Roopa et al.) to reassert that IE and ES remain largely fragmented, or not formalised in principle. This argument is made even though IE is positioned as the profession best placed to achieve sustainability narratives in practice. Its motivation section then explicitly cites Chapter 5 as having already identified integrated IE-ES knowledge components clustered across the three business execution levels, but flags a specific and consequential shortcoming in that earlier work, that those knowledge components remain theoretical and untested for real-world, practical relevance. Chapter 9 exists specifically to close that gap.

The chapter's literature review introduces three evaluative frameworks that had not featured prominently in earlier chapters and that become central to the analytical apparatus in this study. First, the Sustainable Development Goals, the African Union's Agenda 2063 and the VRIO framework. Each is introduced with a stated advantage and a stated limitation, and each is explicitly connected back to IE, ES and SCA, establishing a research gap around the absence of dedicated, empirical VRIO analyses focused specifically on environmental resources within African or IE contexts.

Relevant research component: The research problem is stated as follows: integrated IE and ES knowledge components lack real-world contextualisation and evaluation for a sustainable competitive advantage in South Africa. The research aim is to conduct multiple use cases on integrated IE and ES knowledge components for a sustainable competitive advantage in South Africa. The central research question asks: "Does UCA provide evidence for the integration of IE and ES for a sustainable competitive advantage?" Three research objectives support this aim: to cluster integrated IE and ES knowledge that ensures an SCA; to identify relevant use cases according to that clustering; and to perform the use case analysis against SCA and sustainability frameworks or guidelines. Structurally, this places Chapter 9 in a direct testing relationship with Chapter 7: where Chapter 7 asked how IE and ES knowledge could be integrated into a framework, Chapter 9 asks whether the integrated knowledge holds up against independently published, real-world evidence.

Methodology: Chapter 9 adapts Use Case Analysis (UCA), a method more conventionally associated with software requirements engineering and validation, repurposing it here as a qualitative systems-mapping technique for sustainability research. The chapter justifies this adaptation by citing prior sustainability-science literature on qualitative systems mapping as an approach that enhances rigour and comparability when integrating diverse knowledge for complex problems. It is strengthened further by citing prior precedent for framework-based and metric-based use case evaluation. Eight published, real-world case

studies were sourced through ScienceDirect and Google Scholar and organised into four thematic clusters of two use cases each: circular economy and Lean Six Sigma frameworks; regional circular economy transitions; sustainable value and decisions; and digital and green supply chain management, spanning South Africa, other African nations, and selected international contexts. These coincide with generalisable themes for each side of the TD artefact.

Each of the eight use cases was then evaluated against three distinct frameworks in sequence. First, a knowledge-component correlation matrix mapped each use case against the specific strategies, theories and methods/practices located on each side of the TD artefact in Chapter 7. Second, each use case was assessed for its alignment with specific SDGs and, separately, with the African Union's Agenda 2063 goals. Third, and most rigorously, each use case was formally scored against the VRIO framework and against the three phases of Dynamic Capabilities theory (sensing, seizing, transforming). This configuration creates evidence for each score drawn directly and specifically from the text of the original published case study. This three-layer evaluative structure becomes a methodological contribution as well.

Core findings: Across the eight use cases (covering topics from a Lease & Sell circular economy business model and Lean Six Sigma-enhanced wastewater treatment, through circular plastic economy transitions in Africa and industrial symbiosis in Mpumalanga, to sustainable product life-cycle design, fuzzy-logic supplier evaluation in mining SMEs, and digitalised green supply chains in the South African automotive sector), the correlation matrix showed that UC1a (the Lease & Sell circular economy model) demonstrated the highest overall conformance with the pyramid fountain's knowledge components, while knowledge components tied to the Resource-Based View, socio-technical transitions, Six Sigma and corporate social responsibility were comparatively under-represented across the sample. Every one of the eight use cases could be mapped to at least one SDG, with SDG 12 (responsible consumption and production) and SDG 13 (climate action) recurring most frequently, and three of the twenty African Union 2063 goals (covering standard of living, environmentally sustainable and climate-resilient economies, and world-class infrastructure) were shown to be directly served by at least one use case each.

The VRIO assessment found that all eight use cases demonstrated conformance across all four VRIO criteria, evidencing genuine value, rarity, inimitability and organisational capacity in each published case. The Dynamic Capabilities assessment similarly found that all eight use cases could be mapped onto the sensing, seizing and transforming phases, even though only one use case (UC4a) explicitly used dynamic capabilities language itself, suggesting the underlying theoretical logic is present in practice even where the vocabulary is absent. In combination, these three layers of evidence lead the chapter to answer its own central research question affirmatively: use case analysis does provide evidence that the integration of IE and ES knowledge can produce a genuine sustainable competitive advantage.

Reflections: The principal contribution of this chapter is that it provides independently published, real-world evidence for the first time, rather than relying solely on the data collected in preceding stages of the research. This is a methodologically important step precisely because it is external: the eight use cases were not generated by the own research process itself, but drawn from independently peer-reviewed publications. This creates validation as a degree of external corroboration which chapter 7 did not address. The triple-framework evaluation structure (knowledge-component conformance, SDG/Agenda 2063 alignment, and VRIO/Dynamic Capabilities scoring) is also a genuinely rigorous design, since it tests the artefact from three analytically distinct angles rather than relying on a single evaluative lens.

That said, the chapter is explicit that this remains a form of secondary, retrospective validation rather than prospective, co-implemented testing. This is because the use cases were selected and mapped by the researchers after the fact, rather than being generated through direct engagement with the organisations described. The limitations section within this chapter acknowledges this, calling for future empirical validation using robust performance measurement designs and counterfactual comparisons.

Inter-relationships across other chapters: Chapter 9 is structurally downstream of, and directly dependent on, Chapter 7, where its correlation matrix is built explicitly around the TD artefact produced in that chapter - meaning that Chapter 9 cannot be read or understood independently of the TD artefact which features in Chapter 7. It also directly cites and builds upon Chapter 4 and Chapter 5. This leaves Chapter 9 as the host for a single evaluative exercise from Chapters 4, 5, and 7 simultaneously. The VRIO and Dynamic Capabilities frameworks introduced here also connect Chapter 9 directly to the literature review (Chapter 2) and theoretical grounding (Chapter 3), both of which discuss VRIO, the Resource-Based View, the Natural-Resource-Based View, and Dynamic Capabilities as theoretical lenses for sustainable competitive advantage. Finally, the finding from Chapter 9 divulge that the artefact demonstrates strong external conformance, while still calling for further empirical validation, sets up directly for Chapter 10's Confirmatory Focus Group. This chapter extends the validation effort from secondary literature-based analysis to primary stakeholder engagement, and ultimately for the discussion (Chapter 11), which is explicitly framed as joining an academic conversation from the SLR by positioning the results and grounding them with the SLR, interviews and CFG.

A multi-use case analysis for a sustainable competitive advantage using industrial engineering and environmental sustainability knowledge

Meelan Roopa
School of Industrial Engineering
North-West University)
Potchefstroom, South Africa
orcid.org/0000-0002-3852-2192

Rajenlall Siriram
School of Mechanical, Industrial and
Aeronautical Engineering
University of Witwatersrand
Johannesburg, South Africa
orcid.org/ 0000-0003-2824-5715

Abstract— Transdisciplinary knowledge has demonstrated societal and environmental gains. This research explores the notion of a sustainable competitive advantage (SCA) by performing a use case analysis (UCA). The UCA is used to evaluate an integrated knowledge between industrial engineering (IE) and environmental sustainability (ES). This integrated knowledge recommends mechanisms for South Africa, and in this research, generalised for other countries. These components are specific strategies, theories, and methods and practices associated with the three business execution levels. The UCA primarily aligns features of the framework with international and South African literature, with conformance mapped against the knowledge components, Sustainable Development Goals, VRIO framework and three stages of Dynamic Capabilities. These demonstrate that the integration of IE and ES can best advance sustainable competitive advantages for South Africa and the likes of many other developing countries.

Keywords—Industrial Engineering, Environmental Sustainability, Sustainable Competitive Advantage, Use Case Analysis, Sustainable Development Goals, African Union 2063 Goals

I. INTRODUCTION

A. Context

Industrial Engineering is considered a multidisciplinary field that can instil operational gains for organisations by creatively designing integrated solutions that align people, processes and technology by creating balanced value [1].

Sustainability is an imperative concern with growing interest. The most neglected is that of environmental sustainability (ES), since most countries are more concerned with poor energy mixes, societal and economic concerns. However, ES is imperative since it protects the environment, catering for all economic activities [2].

According to Roopa, et al. [3], IE and ES are argued to be largely disconnected. Furthermore, it is the IE that could achieve sustainability narratives [4]. Companies are now turning to a sustainable competitive advantage, often conceptualised as improvements within organisations that allow them

to be environmentally considerate, yet competitive [5, 6].

B. Motivation

Roopa and Siriram [7] were able to consult with industrial engineers and environmental practitioners to identify knowledge components across three tiers owed to the three business execution levels, posed as strategic, tactical and operational. Here, strategies are clustered under the strategic business execution level, theories (concepts) under the tactical, while methods and practices are dedicated to the operational level. This tiered approach introduces a cascading application stream. The work of the siloed IE and ES, and the integrated IE and ES knowledge, is considered in this research as part of the clustering employed in this study from preceding research [3,7]. A notable shortcoming is that this remains theoretical and lacks practical relevance to the various knowledge components. Without this integrated assessment for relevance, the efforts to classify and suggest these knowledge components are futile.

C. Research problem

Integrated IE and ES knowledge components lack real-world contextualisation and evaluation for a sustainable competitive advantage in South Africa.

D. Research aim

This research aims to conduct multiple use cases on integrated IE and ES knowledge components for a sustainable competitive advantage in South Africa.

E. Research question

The central research question can be phrased as follows: Does UCA provide evidence for the integration of IE and ES for a sustainable competitive advantage?

F. Research objectives

The objectives in this research are to:

1. Cluster integrated IE and ES knowledge that ensures a SCA
2. Identify relevant use cases according to the clustering
3. Perform the UCA with SCA and sustainability frameworks or guidelines

The pathway to executing the objectives, answering the research question and addressing the aim is detailed in section III.

II. EXISTING THEORIES & PREVIOUS WORK

A. Sustainable Development Goals

The Sustainable Development Goals (SDGs) are a global policy framework that appears repeatedly in the literature and is discussed here with emphasis on curricular integration, sectoral implementation, and links to engineering practice. This section defines SDGs, highlights one clear benefit and one practical limitation, and explains how SDGs connect to IE, ES, and SCA.

The SDGs are the United Nations' 2030 Agenda goals used as an international reference for social, economic, and environmental development and are explicitly invoked as curricular objectives in engineering education initiatives [8, 9]. An advantage is that SDGs provide a common, multi-dimensional framework that universities and industries can map onto curricula and practice to coordinate sustainability efforts [8, 10]. Yet, the SDGs' broad scope and ambition create challenges for concrete curricular or operational adoption, and analyses report incomplete incorporation into degree syllabi and national strategies

Industrial engineering (IE) is positioned as a key vehicle for operationalising SDG targets through curriculum design and practice. Educational mapping exercises show how IE courses can embed SDG concepts so graduates develop responsibility and capability to implement sustainability in systems and processes [8, 10]. IE topics such as process optimisation, systems design and life-cycle thinking were identified as natural touchpoints for SDG integration [10].

The SDGs frame environmental objectives (e.g., responsible consumption, climate action, etc.) that drive IE and policy priorities toward circular and low-impact production strategies; country-level comparisons emphasise circular economy

transitions and technology adoption as routes to meet SDG targets while addressing resource constraints [9, 10]. Furthermore, SDG alignment motivates circular-economy and resource-efficiency approaches, which IE methods can quantify and implement [9, 10].

Aligning firm capabilities with SDG objectives can create market differentiation and long-term value by embedding resilience and stakeholder legitimacy into operations. The VRIO (Value, Rarity, Inimitability, and Organisation) framework is used to evaluate the internal resources and capabilities of an organisation for a sustainable competitive advantage, coined by Barney [11]. Empirical VRIO applications in sector studies illustrate how internally controlled resources (experience, organisational planning) can produce sustained advantage when aligned with broader strategic aims [12].

It is for this reason that embedding SDG-aligned capabilities into organisational resources is a plausible path to durable competitive positioning.

B. African Union 2063 Agenda

Agenda 2063 is the African Union's long-term strategic vision emphasising structural transformation, regional integration, industrialisation, and inclusive development across the continent [4, 13]. It promotes harmonised policies and regional value chains that can accelerate structural transformation and manufacturing growth across African economies.

One shortcoming of this is that the AU Agenda 2063 goals confront gaps in infrastructure, regulatory harmonisation, technology diffusion and institutional capacity, which may slow implementation [13].

Agenda 2063's industrialisation objectives create demand for industrial engineering capabilities in manufacturing systems design, production planning, and technology adoption (including additive manufacturing) to support localised value chains and skills development [4, 13].

An analyses of Africa's industrial trajectory identify policy coordination and systems-level engineering as critical to shifting activity toward higher-productivity industries. When looking at ES, the AU Agenda 2063 and associated industrial strategies highlight opportunities to pursue sustainable industrialisation: localised manufacturing and advanced production methods

(e.g., additive manufacturing) can reduce logistics emissions and material waste if implemented with sustainability criteria, but these advances require deliberate environmental design and policy safeguards [13]. Nevertheless, the literature flags regulatory and infrastructural barriers that must be addressed to avoid unsustainable industrial expansion [4, 13].

At the continental and firm level, Agenda 2063's focus on regional integration and value chain development can enable firms to gain advantage through access to larger markets, coordinated standards, and localised inputs; however, firms must translate policy space into firm-level capabilities (skills, organised processes, knowledge) to capture persistent advantage within integrated regional markets

C. VRIO framework

VRIO is a resource-based analytic framework assessing whether a resource is Valuable, Rare, Inimitable, and Organised to capture value; it is used to diagnose the potential for sustained competitive advantage and to motivate capability development within organisations [11].

The VRIO framework is featured as a practical tool grounded in the resource-based view (RBV) for evaluating firm resources and capabilities. This section defines VRIO, gives a primary advantage and limitation, and details its intersections with industrial engineering, environmental sustainability, and sustainable competitive advantage. VRIO is a resource-based analytic framework assessing whether a resource is Valuable, Rare, Inimitable, and Organized to capture value; it is used to diagnose the potential for sustained competitive advantage and to motivate capability development within organisations [11].

VRIO provides a concise, internally focused method to identify which resources or capabilities can underpin sustainable advantage and to prioritise investments in the organisation and protection of such resources [11].

However, classic VRIO/RBV approaches can under-emphasise dynamic change and environmental shifts; the literature calls for complementing VRIO with dynamic capabilities or knowledge-based perspectives to handle change and innovation [11].

Industrial engineering contributes directly to developing the kinds of organised, valuable, and hard-to-copy capabilities. Important to note is that

VRIO targets process design, production systems, quality management and organisational planning are concrete resources that IE can create and formalise. Application studies using VRIO in construction firms identify experience and organisational structure as VRIO-qualified resources that delivered competitive advantage in practice, illustrating how IE-type competencies map to VRIO criteria [12, 14].

Applying VRIO to sustainability means assessing whether environmentally oriented practices (e.g., resource-efficient processes, circular-economy capabilities) are valuable, rare, hard to imitate, and integrated into organisation routines. The supplied literature discusses sustainable engineering practices and circular transitions as strategic priorities but does not provide extensive empirical VRIO analyses focused specifically on environmental resources in African or IE contexts; this indicates a gap in the supplied corpus for explicit VRIO-sustainability case studies [10, 11, 15]. VRIO is directly intended to diagnose and explain SCA: when firms possess resources meeting VRIO criteria and maintain organisational structures to exploit them, they can secure persistent performance differentials; empirical sector studies corroborate this mechanism in practice [12, 14]. Combining VRIO diagnostics with IE efforts to institutionalise capabilities offers a pathway to embed sustainability and resilience into long-term competitive positioning.

D. Identified research gaps

While the SDGs and Agenda 2063 provide robust macro-level frameworks for development, a persistent disconnect remains in their operationalisation within industrial engineering curricula and firm-level capabilities, particularly regarding the infrastructural and regulatory nuances of the African context. Furthermore, although the VRIO framework is a powerful tool for diagnosing sustainable competitive advantage, traditional applications often under-emphasise dynamic environmental shifts and lack dedicated empirical focus on environmental resources within local industrial settings. This highlights a significant opportunity for research to bridge the gap between high-level sustainability policies and practical, sector-specific industrial engineering competencies. By mapping internal organisational resources to transdisciplinary sustainability objectives, future studies can refine the diagnostic precision of the VRIO framework and facilitate a

more durable competitive positioning for firms operating within emerging African markets.

III. METHODOLOGY

A. Traditional application

Conventionally, a Use Case Analysis (UCA) is implemented in software solutions, more so during its developmental stages [15]. It is commonly understood that UCA aids in clarifying requirements, designing and testing frameworks [16]. This approach welcomes a vast array of methodological approaches. Scenario development as a use case was employed by Somé [17] for validation purposes. It is for this reason that scenarios will be formulated by theoretically applying the TD artefact that will be derived from this research.

B. Contextualised application

UCA is not a foreign concept to sustainability research, with evidence demonstrating it is widely applied but confronted with challenges associated with methodological rigour and comparability [18]. For this research, qualitative systems mapping is utilised, as it enhances rigour and comparability with systematic, transparent protocols for integrating diverse knowledge concerning complex problems, and as a means of supporting transdisciplinary communication [19]. Given that sustainability challenges are complex [20], qualitative systems mapping is indeed appropriate. As a means of visualising complexity and informing intervention design [21], qualitative systems mapping can cater for dependency and impact mapping. Dependency mapping is an introspective mapping approach to outline the interdependencies among components [22]. Impact Mapping is the converse, serving as an outward-thinking approach which aligns business goals during software development or projects [23].

To ensure comparability, some use-case analysis are measured against frameworks or metrics. España, et al. [24] are testament of a framework-based comparison of use cases to a method evaluation framework. Similarly, Sabharwal, et al. [25] perform metric-based evaluations for a use case diagram complexity metric against a particular framework. Given that this research is housed within sustainability contexts for South Africa while aligned to ensuring an SCA, a similar approach is followed. For context and relevance, the SDGs, the African Union 2063 Goals and Priorities will serve as impact mapping against metrics for sustainability, while the VRIO

framework and Dynamic Capabilities. The sourcing of literature was done by scouring Science Direct and Google Scholar for appropriate, relevant and current work similar to Ayan, et al. [26] that is associated with interdisciplinary research.

IV. USE CASE ANALYSIS

A. Use case analysis clustering

The first cluster of the artefact can also be classified as the circular economy and Lean Six Sigma. The other clusters consider 2) regional circular economy transitions, 3) sustainable value and decisions and 4) digital and green supply chain management. Table 1 outlines the clustering alongside the two use cases sourced for each cluster, totalling eight use cases. The authors, region and focus of the research are also provided.

TABLE 1 UCA CLUSTERING AND INFORMATION

Cluster	Code	Title	Authors	Region or Country	Research Focus
1: CE & LSS Frameworks	UC1a	A simulation-based optimisation approach for network design: The circular economy perspective	Bal and Badurdeen [27]	Turkey / USA	Integrating Product-Service-Systems (PSS) with traditional sales to promote circularity through a "Lease & Sell" model.
	UC1b	An integrated Lean Six Sigma and circular economy framework for enhancing the sustainable performance of a wastewater treatment plant	AlHerimi, et al. [28]	UAE, UK, Egypt, Finland, Bangladesh, Australia	Enhancing operational efficiency and sustainability in wastewater treatment (WWT) plants using LSS and Circular Economy (CE) principles.
2: Regional CE Transitions	UC2a	Socio-Technical Perspective on Transitioning to a Circular Plastic Economy in Africa	Oyinlola, et al. [29]	Africa (Nigeria, Rwanda, Namibia, Zambia, Kenya)	Analysing the shift from linear to circular plastic systems in Africa enabled by digital innovations
	UC2b	An Analysis of Industrial	Dune and Roberts [30]	South Africa	Strategic analysis of industrial symbiosis

Cluster	Code	Title	Authors	Region or Country	Research Focus
		Symbiosis as a Strategic Tool for Integrated Waste Management Plans (IWMPS) in South Africa – A Case Study of Mpumalanga Province		(Mpumalanga)	to improve waste exchange and recycling among industry players.
3: Sustainable Value & Decisions	UC3a	Product life cycle design for sustainable value creation: methods of sustainable product development in the context of high value engineering	Tao and Yu [31]	Global / China	Developing a framework for sustainable product development using life cycle simulation and value modeling.
	UC3b	Multi-Criteria Decision Support for Sustainable Supplier Evaluation in Mining SMEs: A Fuzzy Logic and TOPSIS Approach	Gidiagba, et al. [32]	South Africa	Using Fuzzy Logic and TOPSIS for evaluating sustainable suppliers in the mining sector.
4: Digital & Green SCM	UC4a	Advancing sustainable supply chain management through digitalisation: Insights from the South African automotive industry	Kirsten, et al. [33]	South Africa	Exploring Industry 4.0 technologies (e.g., IoT, Big Data) as enablers for sustainable supply chain management in the automotive industry.
	UC4b	A green profitability framework to quantify the impact of green supply chain management	Coetzee and Bean [34]	South Africa	Developing a framework to quantify how environmental initiatives affect business profitability

Cluster	Code	Title	Authors	Region or Country	Research Focus
		ent in South Africa			y and carbon emissions.

B. Introduction and classification of use cases

The UCA1-4 will refer to each use case clustering, where a and b are associated with the first and second application streams. Therefore, UCA1a refers to the first research paper on the first use case application based on the knowledge components on the side of the artefact. This subsection introduces each use case, accompanied by a brief introduction, mention of relevant knowledge components and the core results.

C. Knowledge component interactions

Using the configured codes and context provided, the following table demonstrates the various knowledge components (KC) which are a derivative of each side of the IE pyramid water fountain model. Each colour coded block suggests a knowledge component conformance.

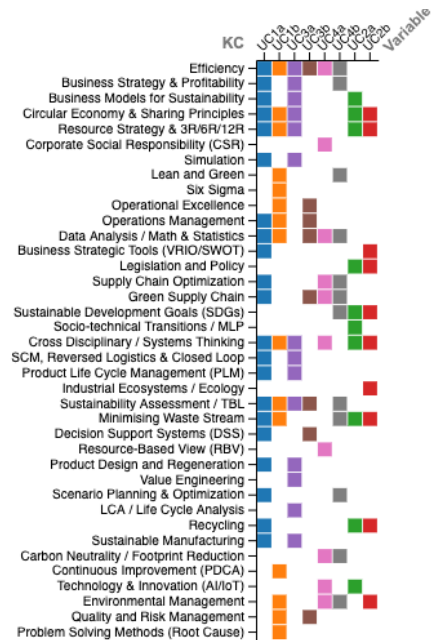


Fig. 1 Knowledge component and UCA correlation matrix

As illustrated by the figure, UC1a demonstrates the highest conformance to the selected knowledge components. Perhaps the knowledge component with the least representation are that tied to the RBV, Socio-technical transitions, Six Sigma and Corporate Social Responsibilities.

D. SDG Alignment

To demonstrate the UCA conformance, each Use Case is discussed and aligned to at least one SDG.

UC1 addresses the environmental crisis caused by the "take-make-consume-dispose" model by proposing a "Lease & Sell" business model. It directly aligns with SDG 11 (Sustainable cities and communities) and SDG 12 (responsible consumption and production) by developing regenerative systems that minimise waste, emissions, and energy consumption. The authors explicitly note that CE strategies are vital for progressing toward the 2030 targets for SDG 1 (No poverty) and SDG 5 (Gender equality) through more inclusive business models.

UC1b integrates Lean Six Sigma (LSS) with CE principles to optimise municipal wastewater treatment (WWT). It is fundamentally aligned with SDG 6 (Clean water and sanitation) by ensuring wastewater meets quality standards for reuse in irrigation and fertiliser production. Furthermore, by focusing on methane (CH₄) recovery to reduce greenhouse gas emissions, the research supports SDG 13 (Climate action).

UC2 investigates how digital niche innovations (like 3D printing and blockchain) can accelerate Africa's transition to a circular plastic economy. The research explicitly maps circular practices to SDG 11, SDG 12, and SDG 14 (Life below water) by tackling plastic pollution, which causes significant environmental and health problems in Africa. It also emphasises SDG 9 (Industry, innovation, and infrastructure) through the deployment of emerging technologies.

UC2b focuses on South Africa's Mpumalanga province. This research explores industrial symbiosis as a tool for waste management. It aligns with SDG 12 by promoting the "waste as a resource" paradigm and SDG 13 by facilitating a "just transition" away from fossil fuels in the world's most coal-dependent economy. The study highlights that these synergies can reduce the carbon footprint and improve the health of flora and aquatic environments.

UC3a proposes a framework for sustainable product development using life cycle simulation (LCS) to maximise multi-stakeholder value. It supports SDG 9 and SDG 12 by translating consumer and business "value requirements" into engineering characteristics that reduce material demands, energy use, and landfill waste.

UC3b develops a decision support system for selecting sustainable suppliers for mining maintenance systems. It aligns with SDG 8 (Decent work and economic growth) by enhancing the operational resilience and competitiveness of small and medium enterprises (SMEs) in the mining sector. It also supports SDG 12 by integrating environmental and social sustainability factors into asset management procurement.

This generic qualitative study (UC4a) explores the role of digitalisation in sustainable supply chain management (SSCM) within the South African automotive industry. It is primarily aligned with SDG 13 and SDG 9, as managers use digital tools to track carbon footprints, reduce waste during production, and report environmental impacts more accurately.

In UC4b, the authors develop a framework to quantify the financial and environmental impacts of green supply chain initiatives. By linking carbon emissions directly to logistics operations and source activities, the framework supports SDG 13 and SDG 12. The research provides a method for businesses to translate green actions into measurable goals, such as 19%–20% reductions in annual carbon emissions.

E. African Union 2063 Agenda Alignment

The eight use cases demonstrate alignment with three out of the twenty AU 2063 Goals dedicated in the following subsections.

1) Goal 1: A high standard of living, quality of life and well-being for all citizens

This goal focuses on transforming African economies through manufacturing, industrialisation, and value addition. UC2a is the most directly aligned, as it investigates niche digital innovations (3D printing, blockchain) to accelerate Africa's transition to a circular plastic economy across five countries. It emphasises that these technologies can compensate for infrastructure deficits and create employment. UC3b aligns by focusing on the operational resilience of Mining SMEs in South Africa, which is critical for inclusive growth in the mineral-rich continent. UC3a and UC1a support this goal by proposing frameworks for high-value engineering and circular business models ("Lease & Sell") that decouple economic growth from resource depletion.

2) Goal 7: Environmentally sustainable and climate resilience for economies and communities

This goal targets the reduction of carbon footprints and the sustainable management of natural resources. UC1b focuses on resource recovery in wastewater treatment, using methane (CH₄) recovery to reduce greenhouse gas emissions and enhance long-term system resilience. UC2b directly addresses the "just transition" away from fossil fuels in South Africa's Mpumalanga province, the world's most coal-dependent economy, by using industrial symbiosis to divert waste from landfills. UC4a and UC4b align by leveraging digitalisation and green supply chain frameworks to track and reduce carbon emissions in the South African automotive and FMCG sectors, which represent the largest contribution to GHG emissions on the continent.

3) Goal 10: World-Class Infrastructure crisscrosses Africa

This goal strives to create infrastructure connectivity and communications for all. UC2a calls for a "common continental approach" to standards for materials, product design, and recycling, reflecting the AU's push for regional integration and shared infrastructure standards. UC4a highlights the role of Industry 4.0 and digital tools in creating smart, transparent infrastructure within supply chains

F. VRIO framework assessment

By evaluating each phase of VRIO, it was found that each of the eight use cases demonstrates conformance. The evaluation and evidence from each paper are supplied in Table 2.

TABLE 2 VRIO FRAMEWORK EVALUATION OF USE CASES

Use Case	Value	Rarity	Inimitability	Organisation
UC1a	Increases gross profit (e.g., S10 scenario) while meeting social utility objectives through product recovery.	Introduces a "novel business strategy" (Lease & Sell) and a unique practical network design strategy.	High complexity in integrating discrete event simulation with multi-objective optimisation models.	Focuses on strategic facility opening decisions and inter-domain alignment for strategy execution.
UC1b	Delivers 6.5% energy reduction, \$48,891 annual savings, and improved	A novel framework tailored specifically to sustainability and climate resilience in wastewater treatment.	Adaptation of established quality tools (FMEA, regression) for environmental infrastructure is	Employs Standard Operating Procedures (SOPs) and incentive programs to institutionalise improvements.

Use Case	Value	Rarity	Inimitability	Organisation
	climate resilience.		underexplored.	
UC2a	Accelerates Africa's circular plastic transition and connects niche innovations to multiple SDGs.	Identifies ten niche digital innovations (e.g., AI, Blockchain) specifically for the African socio-technical landscape.	Progress is slowed by regime-level lock-ins, fragmented regulation, and funding deficits.	Highlights the need for stakeholder collaboration platforms and robust data-tracking systems.
UC2b	Mitigated 1.7 million tons of GHG emissions and achieved R129 million in landfill cost avoidance.	Investigates industrial symbiosis in Mpumalanga, the world's most coal-dependent economy.	Barriers include regulatory red-tape, lack of technical expertise, and fractured policy integration.	Proposes incorporating synergies into legislated Integrated Waste Management Plans (IWMs).
UC3a	Maximises multi-stakeholder value; reduces material demands (91.89%) and landfill waste (18.44%).	Provides tools that translate sustainable value requirements into meaningful engineering characteristics.	Complexity of modeling complicated closed-loop life cycles using Life Cycle Simulation and QFD.	Brings experts in engineering, management, and ecology to a common vision of value.
UC3b	Selection of reliable CMMS suppliers helps optimise equipment, energy, and materials.	Introduces a hybrid Fuzzy Logic and TOPSIS model for sustainable supplier evaluation in mining.	Uses fuzzy numbers to address the uncertainty and subjectivity of expert evaluations.	Offers practical guidance to align software procurement with broader sustainability goals.
UC4a	Improved operational efficiency (reduced error, faster turnaround) and carbon emission reduction.	Provides organisations with a potential "first-mover" advantage in the South African automotive market.	Barriers like load shedding, skills shortages, and internal resistance to change hinder imitation.	Requires managers to prioritise employee training and cultivate a culture that embraces digital change.
UC4b	Quantifies financial impacts (ZAR 1m savings) and environmental benefits (20%)	Currently no other single framework addresses both profitability and sustainability indicators in	Requires high granularity of financial data (actual ledger/expense data) for accurate	Designed to monitor actual performance against predetermined estimates for strategic planning.

Use Case	Value	Rarity	Inimitability	Organisation
	emission reduction).	the complete chain.	quantification.	

G. Dynamic capabilities assessment

Similar to the VRIO assessment, the three primary phases of dynamic capabilities (sensing, seizing and transforming) are evaluated using the eight use cases. This evaluation has been summarised using Table 3.

TABLE 3 USE CASE ALIGNMENT WITH DYNAMIC CAPABILITY PHASES

Use Case	Sensing (Identifying)	Seizing (Addressing)	Transforming (Realigning)
UC1a	Sensing temporal variations/demand.	Optimised network design for PSS.	Shifting to regenerative "Lease & Sell" models.
UC1b	Forecasting hydraulic capacity risks.	Integrating LSS-CE in DMAIC cycles.	Creating SOPs for lasting operational changes.
UC2a	Identifying 10 niche digital innovations.	Proposing practical ideas for stakeholders.	Transitioning to circular plastic systems.
UC2b	Identifying legislative/governance gaps.	Proposing partnership & funding models.	Reconfiguring coal-dependent waste habits.
UC3a	Mapping sustainable value requirements.	QFD solutions for artifact design.	Life cycle simulation for continuous innovation.
UC3b	Identifying sustainable supplier criteria.	Ranking suppliers via Fuzzy-TOPSIS.	Eliminating complexity via Industry 4.0.
UC4a	Responding to sustainability pressures.	Adopting advanced tools (AI, IoT, Robotics).	Transforming traditional processes & culture.
UC4b	"As-is" cost and emission assessments.	Quantifying green initiative impacts.	Monitoring performance to sustain profitability.

This demonstrates that the knowledge components, use case alignment and overall conformance with evaluation frameworks hallmark a sustainable competitive advantage. This is further articulated by demonstrating the ability to sense, seize and transform resources for competitive and sustainable advantages in a changing environment. While only UC4a explicitly mentions dynamic capabilities, the methodologies and frameworks

across all eight use cases directly align with the three primary phases.

V. DISCUSSION

A. Research aim, question and objectives

This research performed a multiple use case analysis on integrated IE and ES knowledge components for a sustainable competitive advantage. The research question does indeed demonstrate that a UCA is able to integrate and demonstrates an SCA given the high conformance across the knowledge components, VRIO and DC performance. The first objective sought to effectively cluster the integrated knowledge. Next, relevant use cases were identified as part of objective two. Finally, the final objective was to comprehensively evaluate the use cases against various frameworks and guidelines.

B. Match and contribution

The papers collectively explore how Industry 4.0 and digital tools act as critical enablers for sustainability transitions across diverse sectors. A core strength of these studies is the development of structured methodologies to solve complex engineering and management problems. The research provides critical insights into the "landscape pressures" and systemic bottlenecks that hinder sustainable progress. The papers redefine value creation by moving beyond traditional profitability to include environmental and social utility—the Triple Bottom Line.

VI. CONCLUSION

A. Concluding remarks

This research was able to demonstrate the novelty in integrating IE and ES for an SCA. UCA is showcased as an effective means to test out relevance and conformance using real-world published literature on case studies.

B. Limitations and recommendations

Given that this research only explored some of the identified knowledge components. More work can be done to implement dual initiatives that begin with the integrated IE and ES venture from the onset. Work can also be done to explore this in developed and developing countries.

Future research should prioritize rigorous empirical validation by implementing robust performance measurement designs and counterfactual comparisons. Utilizing statistical or simulation-based methods will enable the

quantification of the framework's systemic impact while verifying its core theoretical claims. These data-driven efforts are vital to stress-test the model's efficacy across diverse sectors and ensure a successful transition from theoretical constructs to industrial practice. Another shortcoming is that a more comparative, large scale scoring approach could be used to assess more use cases aligned to specific sectors. The high conformance to various assessment frameworks could also be tested by developing specific SCA methodologies geared towards being measured in this structure.

REFERENCES

- [1] H. Darwish and L. Van Dyk, "The industrial engineering identity: from historic skills to modern values, duties, and roles," *South African Journal of Industrial Engineering*, vol. 27, no. 3, pp. 50-63, 2016.
- [2] S. Al-Ghamdi, M. Qureshi, N. Almakayeel, M. Mansour, and S. Abdul Khadar, "An approach to attaining sustainability by enhancing the environmental factors that affect the quality of urban life," *South African Journal of Industrial Engineering*, vol. 34, no. 1, pp. 42-60, 2023.
- [3] M. Roopa, R. Siriram, and R. Coetzee, "Exploring Industrial Engineering Knowledge and Environmental Sustainability," *Sustainability*, vol. 16, no. 17, p. 7392, 2024. [Online]. Available: <https://www.mdpi.com/2071-1050/16/17/7392>.
- [4] T. Tsoku, L. van Dyk, and W. Maisiri, "The role of industrial engineering and its impact on sustainability: a systematic review approach," *South African Journal of Industrial Engineering*, vol. 35, no. 3, pp. 70-79, 2024.
- [5] M. Srivastava, A. Franklin, and L. Martinette, "Building a sustainable competitive advantage," *Journal of technology management & innovation*, vol. 8, no. 2, pp. 47-60, 2013.
- [6] B. Nunes, D. J. Bennett, and D. Shaw, "Building a competitive advantage through sustainable operations strategy," 2013.
- [7] M. Roopa and R. Siriram, "Identifying harmony between industrial engineering and environmental sustainability in South Africa," *Sustainable Futures*, vol. 11, p. 101695, 2026/06/01/ 2026, doi: <https://doi.org/10.1016/j.sfr.2026.101695>.
- [8] G. Bracho, A. M. Pedrosa, E. Klyatskina, J. Maheut, S. Bernal-Perez, and J. Giner-Navarro, "Analysis of the integration of Sustainable Development Goals in the industrial engineering degree course," *Multidisciplinary Journal for Education, Social and Technological Sciences*, vol. 10, no. 1, pp. 1-22, 2023.
- [9] M. L. Brunetti, G. Teixeira, M. de Castro, and L. F. Lara, "Sustainable competitive advantage in construction: study of central region of Paraná," *REBRAE*, vol. 8, no. 2, pp. 212-228, 2015.
- [10] O. Sibanda, "AfCTA and the trajectory of industrialisation and development sustainability in Africa," *Koers: Bulletin for Christian Scholarship= Koers: Bulletin vir Christelike Wetenskap*, vol. 85, no. 1, pp. 1-10, 2020.
- [11] J. Barney, "Firm resources and sustained competitive advantage," *Journal of management*, vol. 17, no. 1, pp. 99-120, 1991.
- [12] M. S. Hoosain, B. S. Paul, W. Doorsamy, and S. Ramakrishna, "Comparing South Africa's sustainability and circular economic roadmap to the rest of the world," *Materials Circular Economy*, vol. 5, no. 1, p. 2, 2023.
- [13] D. Klenam et al., "Toward sustainable industrialization in Africa: the potential of additive manufacturing—an overview," *Frontiers in Manufacturing Technology*, vol. 4, p. 1410653, 2025.
- [14] A. Henry, "The internal environment: A resource-based view of strategy," *Understanding strategic management*, pp. 124-150, 2008.
- [15] G. Schneider and J. P. Winters, *Applying Use Cases: A Practical Guide*. Pearson Education, 2001.
- [16] F. Zhu and W.-T. Tsai, "Framework-oriented analysis," in *Proceedings. The Twenty-Second Annual International Computer Software and Applications Conference (Compsac'98)*(Cat. No. 98CB 36241), 1998: IEEE, pp. 324-329.
- [17] S. S. Somé, "Use cases based requirements validation with scenarios," in *13th IEEE International Conference on Requirements Engineering (RE'05)*, 2005: IEEE, pp. 465-466.
- [18] P. B. Corcoran, K. E. Walker, and A. E. Wals, "Case studies, make-your-case studies, and case stories: a critique of case-study methodology in sustainability in higher education," *Environmental Education Research*, vol. 10, no. 1, pp. 7-21, 2004.
- [19] S. Hanger-Kopp, L. K.-G. Lemke, and J. Beier, "What qualitative systems mapping is and what it could be: integrating and visualizing diverse knowledge of complex problems," *Sustainability Science*, vol. 19, no. 3, pp. 1065-1078, 2024.
- [20] J. H. Allen, F. Beaudoin, E. Lloyd-Pool, and J. Sherman, "Pathways to sustainability careers: building capacity to solve complex problems," *Sustainability: The Journal of Record*, vol. 7, no. 1, pp. 47-53, 2014.
- [21] N. P. Pronk and B. Y. Lee, "Qualitative systems mapping in promoting physical activity and cardiorespiratory fitness: perspectives and recommendations," *Progress in Cardiovascular Diseases*, vol. 83, pp. 43-48, 2024.
- [22] J. Li et al., "A business process-driven approach for requirements dependency analysis," in *International Conference on Business Process Management*, 2012: Springer, pp. 200-215.
- [23] G. Adzic and M. Bisset, *Impact Mapping: Making a big impact with software products and projects*. Provoking Thoughts Limited, 2012.
- [24] S. España, N. Condori-Fernandez, A. González, and Ó. Pastor, "An empirical comparative evaluation of requirements engineering methods," *Journal of the Brazilian Computer Society*, vol. 16, no. 1, pp. 3-19, 2010.
- [25] S. Sabharwal, P. Kaur, and R. Sibal, "Empirical and Theoretical Validation of a Use Case Diagram Complexity Metric," *International Journal of Information Technology and Computer Science*, vol. 9, no. 11, pp. 35-47, 2017.
- [26] S. Ayan, N. Ivanova, S. Ivanova, and S. Ivanchikov, "Evaluating the Effectiveness of Google Scholar, ScienceDirect, Mendeley, and eLibrary for Interdisciplinary Research," *South-east European forestry: SEEFOR*, vol. 16, no. 2, pp. 227-238, 2025.
- [27] A. Bal and F. Badurdeen, "A simulation-based optimization approach for network design: The circular economy perspective," *Sustainable Production and Consumption*, vol. 30, pp. 761-775, 2022/03/01/ 2022, doi: <https://doi.org/10.1016/j.spc.2021.12.033>.
- [28] N. AlHerimi, M. Shamsuzzaman, J. Antony, S. Haridy, A. Shamsuzzoha, and A. Karim, "An integrated Lean Six Sigma and circular economy framework for enhancing the sustainable performance of a wastewater treatment plant," *The TQM Journal*, pp. 1-26, 2026.
- [29] M. Oyinlola et al., "A socio-technical perspective on transitioning to a circular plastic economy in Africa," Available at SSRN 4332904, 2022.
- [30] T. C. Dune and H. Roberts, "An Analysis of Industrial Symbiosis as a Strategic Tool for Integrated Waste Management Plans (IWMPS) in South Africa—A Case Study of Mpumalanga Province," *Journal of Circular Economy*, vol. 4, no. 1, 2026.
- [31] J. Tao and S. Yu, "Product life cycle design for sustainable value creation: methods of sustainable product development in the context of high value engineering," *Procedia cirp*, vol. 69, pp. 25-30, 2018.
- [32] J. O. Gidiagba, M. Okwu, and L. Tartibu, "Multi-criteria decision support for sustainable supplier evaluation in mining SMEs: A fuzzy logic and TOPSIS approach," *Logistics*, vol. 9, no. 3, p. 132, 2025.
- [33] M. Kirsten, S. Mthethwa, T. Sitsha, and W. Niemann, "Advancing sustainable supply chain management through digitalisation: Insights from the South African automotive industry," *Journal of Transport and Supply Chain Management*, vol. 19, p. 1221, 2025.
- [34] N. Coetzee and W. L. Bean, "A green profitability framework to quantify the impact of green supply chain management in South Africa," *Journal of Transport and Supply Chain Management*, vol. 10, no. 1, pp. 1-15, 2016.

Chapter 10

Confirmatory Focus Group

10 Confirmatory focus group

10.1 Introduction

The confirmatory focus group (CFG) was used to validate the design of the IE pyramid fountain. The CFG was also used to validate the problem. This chapter will delve into the technical details of the CFG itself as well as the results and findings obtained as part of objective four. Before commencing, additional reflection points are made on the UCA performed.

10.2 Use Case Analysis (UCA) reflection

The Use Case Analysis (UCA) elaborated on in Chapter 3 explains the use of Qualitative Systems Mapping as the over-arching approach to articulate the findings. The execution of the UCA features as a *conference paper* as part of Chapter 9. As mentioned in this conference paper, eight use cases are presented. Further analysis reveals four papers with explicit quantified improvements that are presented in Figure 31.

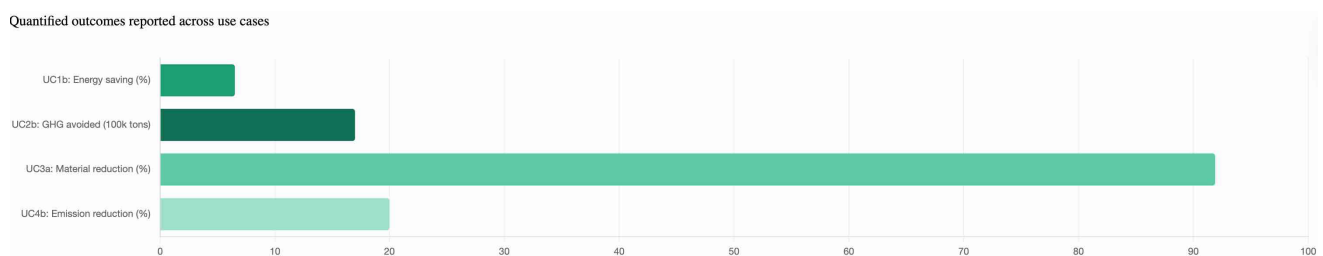


Figure 29 Quantified outcomes from four of the eight use cases

The energy saving use case UC1b presented a minor contribution towards sustainability. The same is said for UC2b with minor GHG emissions, alongside UC4b with only 20% GHG reduction. UC3a boasts over 90% material reduction. Collectively, this result demonstrates the ability to address energy savings, GHG emissions and material consumption if combined holistically. Given that the TD artefact summates the various knowledge components, it suggests that these sustainability metrics can also be addressed in real-world contexts.

Another perspective is to reflect on the SDG distribution across the eight use cases as evidenced in Figure 32.

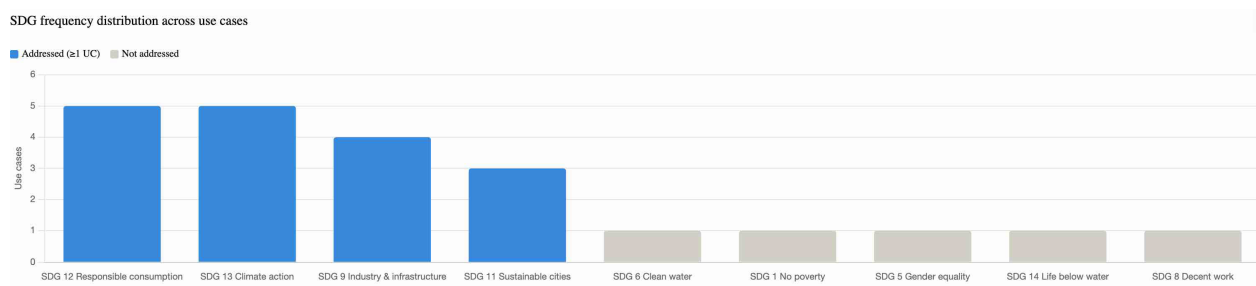


Figure 30 SDG distribution across eight use cases

As can be seen from the visual, the strongest associations are with SDGs 12, 13, 9 and 11. The weakest are with SDG 1, 5, 6, 8 and 14 with several not having been linked to any of the eight case studies.

10.3 CFG method and event details

As per the CFG agenda defined in Chapter 3, a welcoming was performed where participants were allowed to introduce themselves to the group, their area of specialisation and associations with IE and environmental sustainability.

The researcher obtained verbal consent from each participant to record the session and make use of the transcript feature. Pseudo-anonymisation was used to create classifiers for each participant. A total of six participants were available and willing to partake in the CFG, conforming with the acceptable lower bounds of four or six participants as prescribed by Morgan (1996) and Monica Chiarini *et al.* (2010).

The CFG followed the agenda prescribed in Chapter 3, specifically in Table 8. The CFG then followed with a 12-minute presentation where the researcher presented the research problem, methodology and design logic used for the framework according to the ACD methodology. The artefact was demonstrated, and participants were briefed on the pyramid side allocations and some of the cascading streams by showcasing the alluvial diagrams, water analogy, pyramid and Zwicky box inspiration, sunburst diagram and each side of the IE Pyramid Water Fountain.

The evaluation included a three-minute survey that was shared using a QR code which allowed participants to complete a Google Forms survey that incorporated the six survey statements verbatim. The remaining time was dedicated to the four discussion topics that welcomed participation from all participants. At the end, participants were thanked for their contributions to the discussion and the research.

10.4 CFG data and analysis

The following subsections serve as an exposition of the CFG results and findings which include the survey results and discussions tied to various topics evaluating the artefact designed in this study. The format of this was a more formalised, structured approach in accordance with an approach from Hartman (2004), arguing that this combines structured interviewing techniques with group dynamics in a way that generates rich, interactive data.

10.4.1 Survey data

Table 14 provides the survey results. The results contain the pseudo-anonymised respondent denoted FGP1-6. This notation will be used throughout the chapter as a referencing mechanism. The survey results are accompanied by the average and standard deviation used for interpretation thereafter.

Table 14 CFG Survey results

Survey statement	Respondent						Descriptive statistics	
	FGP 1	FGP 2	FGP 3	FGP 4	FGP 5	FGP 6	Average	Standard deviation
ST1. Research problem: The knowledge of industrial engineering and environmental sustainability currently remains disconnected with organisations unable to successfully adopt environmental sustainability	5	4	4	4	2	4	3.8	0.98

Survey statement	Respondent						Descriptive statistics	
	FGP 1	FGP 2	FGP 3	FGP 4	FGP 5	FGP 6	Average	Standard deviation
for a sustainable competitive advantage in South Africa.								
ST2. The framework demonstrates knowledge that is from industrial engineering	5	5	5	5	5	5	5.0	0
ST3. The framework demonstrates knowledge that is from environmental sustainability	4	5	4	4	5	5	4.5	0.55
ST4. The framework demonstrates cascading and aligns with the business execution levels	4	5	4	4	4	5	4.3	0.52
ST5. The framework demonstrates mechanisms to ensure a sustainable competitive advantage in South Africa	5	5	3	4	3	4	4.0	0.89
ST6. The framework addresses the research problem	5	5	5	5	4	5	4.8	0.41
Grand mean:							4.5	
Average standard deviation:							0.5	

The results indicate a grand mean of 4.5 on the 5-point Likert scale, indicating that consensus has been reached on the six statements. It was unanimous that the framework embodies IE knowledge. This is indicative that this artefact is representative of IE and was further supported by a 4.5 average of demonstrating knowledge tied to ES. The research problem was found to be the most contested statement. However, this still scored an average above 3.75. A score on a 5-point Likert scale of more than 3.75 (75%) as a survey aggregate motivates consensus. Furthermore, an average deviation index of less than 0.8 suggests an acceptable interrater agreement (Burke & Dunlap, 2002).

Barriers, enablers, future research, improvements, limitations and terms of validation were the six codes configured and used to perform the thematic analysis in atlas.ti, Table 15 represents the co-occurrence densities between the previously mentioned codes and their sentiment.

Table 15 CFG Sentiment analysis and code density co-occurrence

Code	○Sentiment: Negative Gr=7	○Sentiment: Neutral Gr=36	○Sentiment: Positive Gr=8
○Barriers Gr=11	2	9	1
○Enablers Gr=4	0	3	0
○Future research Gr=12	1	10	3
○Improvements Gr=6	1	3	2
○Limitations Gr=10	2	6	2
○Validation Gr=10	1	7	2

For the negative sentiment, the minority meets the validation theme, followed by improvements and limitations. This is indicative of high consensus and strong validation of the TD artefact. With regards to neutrality, this was the most common sentiment, far reaching across all of the themes. However, the largest Sankey relationship is a neutral sentiment towards future research directions, implying mixed perception on future avenues. Finally, the positive sentiment is relatively spread across all themes. As expected, the least positive associated with the barriers. It becomes apparent that there was limited sentiment on the enablers from the CFG discussions. Participants suggested many neutral future research avenues and validation points. There is also a set of limitations confessed by participants. A simplistic method of understanding the nature of text is to explore the word cloud of terms used in the transcript. Figure 33 depicts this aforementioned word cloud.



Figure 31 Word cloud of CFG transcript data

As can be seen from the diagram, many of the conversations explored 'framework', 'pyramid' and the various knowledge components. The advantages of the pyramid were prevalent amongst participants. Additional terms considered the various sides of the words 'pyramid', 'water' and 'South Africa' in a specific context.

The same set of data can be further critiqued by stepping into the analysis and evaluating the text coded. Figure 34 provides this step in the analysis.



Figure 32 Word cloud of CFG transcript-coded data

There is a slight variation noted between the CFG raw data and coded data during the analysis. The word 'advantage' is more popular and the term 'disconnect' is featured more. The mention of the term 'environment' was lessened while new terms such as 'carbon', 'penalty' and 'international' emerged from the word cloud. The built-in atlas.ti sentiment analysis consolidated the same coded data and was able to render a flow analysis on the codes. This illustration is provided in Figure 35.

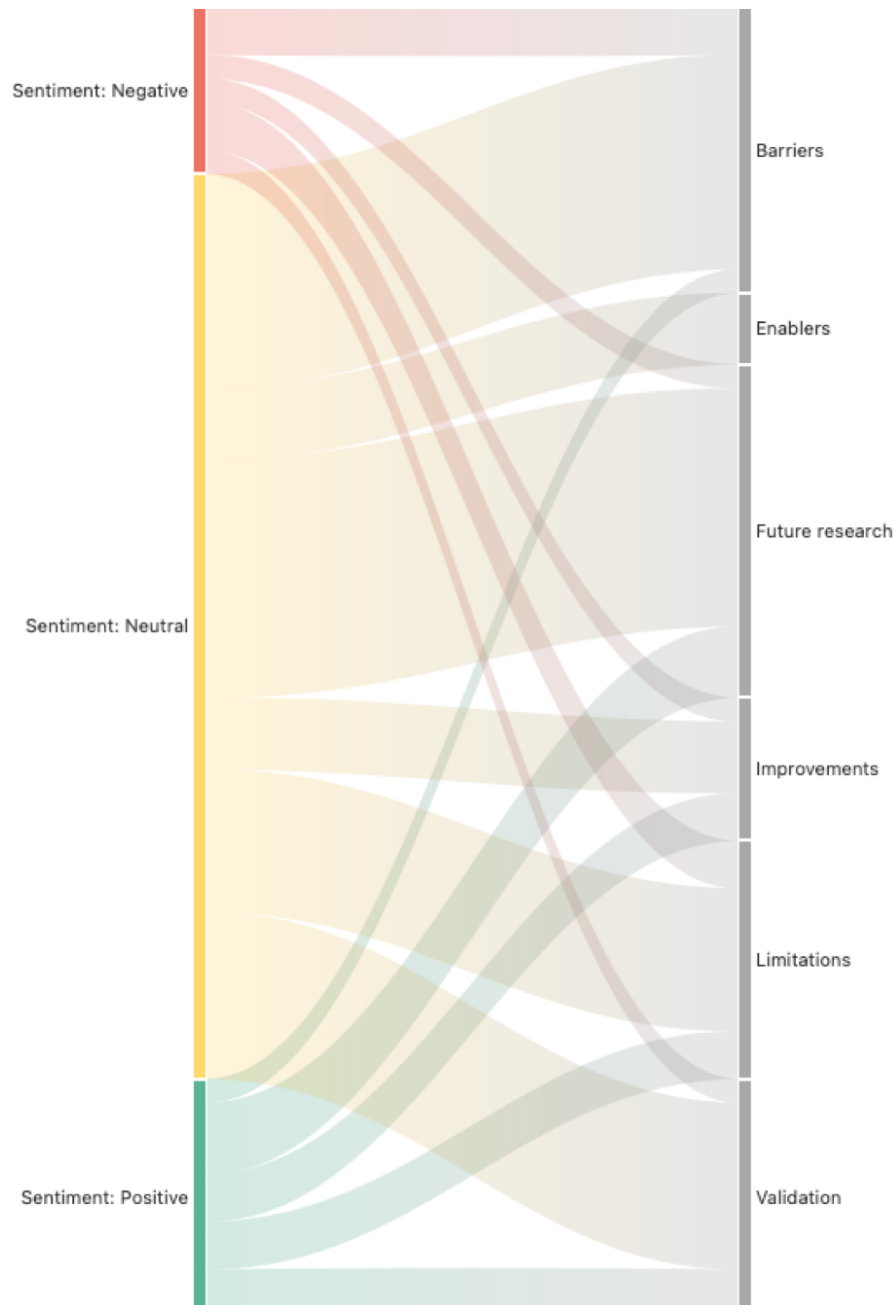


Figure 33 Sankey diagram of sentiment analysis and codes from CFG

The core data was deemed neutral across the 6 codes configured for the analysis. No negative or positive sentiment was traced to the enablers, while improvements were deemed mostly positive or neutral in their phrasing.

10.4.2 Discussion topic 1 findings

Discussion topics welcomed qualitative data analysed using atlas.ti. Appendix F serves as a sample of the CFG data obtained during this interaction with participants. Discussion

topic 1 was, “To what extent do you believe this framework addresses the aforementioned research problem?”.

Focus Group Participant 1 (FGP1) declared that the framework and its ability to solve the problem do, indeed, match. This reaffirms that the solution solves the research problem. However, some critique from FGP2 was that this is perhaps still more on an international level since South Africa has a unique environment and infrastructure needs. This was followed by a follow-up on from FGP3 stating that context specificity is crucial. The participant also mentioned that the disconnect in sustainability concepts, tools, techniques and approaches does exist and the framework “... definitely does bring those closer together ...”. FGP3 also mentioned that the solution needs to advise more on the selection process for the organisation.

The mean score of 4.8 suggests that the solution does, indeed, address the research problem, but the South African context can be improved since there is a nuanced industry, infrastructure and environment tied to sustainability objectives (FGP2). However, the same set of participants formed part of the interviews and resided in South Africa. Furthermore, the survey results validated the research problem.

FPG6 gave recognition that the framework does theoretically address the identified research problem by also declaring that “I think this gives a fantastic overview of everything”. However, the participant stated that it does require practical application with skills acquisition within organisations. FPG6 continued to profess that this aspect of the research might fall outside the scope of the study. In response, the author professed that the framework is a transdisciplinary solution to achieve a sustainable competitive advantage using IE and environmental sustainability knowledge components. It does, in fact, account for practical aspects but much of the content within the framework was informed by literature and grounded by industry (relevance cycle of DSR) using the interviews. Since it is more concerned with the connection between the knowledge components, the skills acquisition process falls outside the scope of the study.

FGP4 mentioned that “... this is a really good stock take of all the strategies, theories and methods and practices that there are”. The participant continued to suggest that the presentation covered ranking or low-hanging fruit application streams. Given that this is an interpretive system that is not sector-specific, the onus lies with the organisation to select and apply the relevant application stream informed by the framework. The framework only suggests the preferred application streams, given the theme of each side discussed in Chapter 6.

A noteworthy viewpoint from FPG5 argued that there is also a larger consideration around KPI, financial reporting and the role of the industrial engineer in sustainability objectives. They also echoed the sentiment of FPG6 associated with skills within organisations and that the absence of skills in an organisation will not have a meaningful impact, even if the SCA connections are understood.

10.4.3 Discussion topic 2 findings

Discussion topic 2 explored “What is your opinion regarding the classification of the cascading effect from the framework?”

The cascading effect from the framework refers to the flow of water along dedicated sides of the Pyramid Water Fountain which continuously recirculates upwards and back down.

The flow of water is never consistent, and so opportunities emerge to have organisations follow a new or slightly varied approach to achieve a sustainable competitive advantage.

FGP2 addressed this discussion topic first by stating that “I found it very practical and understandable”. The participant also confirmed that the framework was understandable and intuitive. This reaffirms that the design logic, illustration and interpretation of the framework is deemed appropriate.

A question was posed by FGP6 asking for clarity whether the framework considers the influence of water upwards. The response to FGP6 was that no, the framework does consider reticulation as a means of continuous improvement using the Zwicky box analogy. The framework did not consider backward implications. FGP6 replied that this could resemble feedback from the SCA initiative on lessons learnt, since this could cause the organisation to consider a new direction or state based on the upward influence and direction. This was accompanied by a similar viewpoint from FGP1, who argued that the boundary definition and movement of water down the pyramid will result in energy distributions. The boundaries set out by the structure and knowledge component contribution can create stress points along the pyramid, which can overburden parts of the framework with repetitive application streams struggling to reticulate upwards due to misaligned communication and feedback before the new SCA initiative.

The water reticulation extended beyond the design logic and application stream analogy using cascading. The inclusion of this would have created duplicated code frequencies, contradicted the knowledge application stream cascading effect adopted in the research and resulted in vague backward streams since many, if not all elements within the framework could have possible effects on the preceding knowledge component. If efforts were made to simplify this approach, it would have resulted in the application stream values merely being doubled. The net effect of this would ultimately skew the Pareto slicing applied in the combination reductions, applied to the alluvial and sunburst diagrams.

FGP4 also rallied on the upwards water reticulation by stating that a pump mechanism for the framework can resemble methodological steps and strategic intent behind new initiatives. The example considered carbon foot printing, which was linked with the purpose of decarbonisation. The question posed for argument’s sake was, “Why do we want to decarbonize?”, which participant 4 answered by mentioning that this could be to better align with the SDGs. This example demonstrates that the logic for new strategic intent can be backtracked or reverse-engineered by starting with a specific method or practice, considering a theory and then aligning to a strategy.

10.4.4 Discussion topic 3 findings

Discussion topic 3 considered “Why do you believe this framework can promote environmental sustainability and ensure a sustainable competitive advantage?”

FGP1 articulated that one of the biggest challenges with the topic is that the development sees engineering and conservation as siloed facets that pin industry against the environment and vice versa. The argument was further stressed that engineers and environmental scientists need to innovate solutions for the future with each other and not for each other. Collaboration and cross-skills during these efforts may help bridge the supply chain by bringing suppliers and consumers closer to each other. This further lends itself to a more competitive advantage being formulated for the organisation, against its competitors.

The phrasing of the discussion topic was queried by FGP6, who advised that it is challenging to “ensure” a sustainable competitive advantage, but rather that the framework can support, facilitate or contribute towards a sustainable competitive advantage. The participant voiced that the framework can “... contribute towards, support and facilitate ...” an SCA and that “... no single framework can ensure a sustainable competitive advantage”. This argument is acknowledged. However, the research philosophy defined by the research onion in Chapter 3 argues that a positivist paradigm is adopted. FGP4 harmonised with this by suggesting that “ensure” may be the more acceptable phrasing. The framework capability is modified to “facilitate” a sustainable competitive advantage and not explicitly “ensure”, since sustainability research has no universal solution (FPG6).

FGP4 challenged the assumption of whether ES ensures a competitive advantage. The evidence against this was that in South Africa, price is a crucial factor while ES remains an external or secondary objective. For example, if you are not being carbon taxed, your organisation may still conduct activities which pose a negative effect on the environment.

Another suggestion on the phrasing of this discussion topic emanated from FPG6 who tried to clarify that the intent of this topic was to argue the extent to which ES and a competitive advantage are co-promoted or co-supported by each other.

10.4.5 Discussion topic 4 findings

Discussion topic 4 focused on “What suggestions would you make to improve the framework?”

Across the preceding discussion topics, participants had pre-emptively started providing suggestions on the framework before the discussion topic featured. In summary, the researcher relayed the already-suggested improvements as follows:

- a) Defining the role of industrial engineers within sustainability contexts using the framework
- b) The broader context selection priority or decision support system that the framework can be further developed on
- c) A water pump analogy to the framework that demonstrates the way in which water would reticulate and interact upwards
- d) A prioritisation or weighting of water according to the frequency

Prioritisation has been used to modify the cascading stream by having a heat-map representation. However, implementing this would create bias in the framework and go against the constructivist nature of this artefact.

A new suggestion from FGP4 was to consider a slice or additional indication on the pyramid which demonstrates the South African perspective, since several of them are more aligned to aspects from the global north. This critique was substantiated by the argument that carbon capture will only become relevant in the next ten years.

FGP 5 observed that the framework interpretation has duality in its application and that their understanding differed from FGP1. FGP5 also confessed that focus groups truly allow one to see an alternative perspective, and that FGP1 1 believed that the nature of the study was to bring sustainability into IE. Whereas FGP5 saw this the other way, that IE was being brought into the sustainability paradigm. It was further suggested that the framework should achieve both, which corroborates the notion of this research having

produced a transdisciplinary framework despite FGP1 and FGP5 having polar interpretations. This statement prompted FGP1 to respond to the observation. FGP1 replied that their understanding of the framework suggested that the IE and environmental sustainability arenas do not need to oppose each other, but rather, that both can co-exist. The candidate also mentioned the CNEFIN model that can assist with perspective.

It was also mentioned by FGP 1 that frameworks and high levels of complexity require a simple solution. However, as a framework evolutionary trait, it becomes a product of its predecessors by incorporating more than one aspect that overlaps and superimposes one another. FGP1 advised that it is important to understand the various models and how they interact with one another before extracting behaviours and creating one's own artefact.

FGP6 stated that another way of improving the framework is to present the operationalisation of the framework. For example, provide a step-by-step guide to walk organisations through the decision making and practical rollout of the framework. This sparked a remark by FGP3 who mentioned that the inclusion of environmental sustainability or a competitive advantage is normally one or the other. The participant complimented the synergetic relationships the framework suggested: that the knowledge application streams with high synergy can be emphasised differently. FGP3 also shared with the panel that industry often loses sight of the synergy that could exist, given that investment drives the decisions organisations make to remain competitive. This led FGP3 to concur with the suggestion of providing process steps for industries to be able to internalise the framework and apply it in their organisation. Another sentiment shared on the framework was that the audience or end-user of the framework is also important to keep in mind.

Focus Group Participant 5 (FGP5) professed that it could also be that the framework does boast the diverse value industrial engineers have, and that it could be that many organisations are not aware of the possibilities of IE. The bigger picture, in fact, is what the role of the Industrial Engineer is when it comes to sustainability.

The backway implications of the water flowing down the pyramid was also not part of the design of the study since the Pareto and sunburst illustrations assumed unidirectional flow cascading across each knowledge component, as dedicated tiers belonging to the Pyramid Water Fountain.

A critique from FGP4 was that the solution addresses and theoretically connects everything but practical application and a rollout strategy are required. It could therefore be that the framework needs to consider its implications and positioning within the knowledge supply chain, IE taxonomy models or other sustainability contexts.

FGP6 mentioned that the skills acquisition process for organisations may be worth exploring in the research. Although this stems outside the scope of the research, the skills aspect is a valid attribute for the eventual rollout of the sustainable competitive advantage effort being made. Skills acquisition from IE and environmental sustainability domains are present in the literature.

FGP6 suggested that the framework can provide a more detailed level within a business context and that organisations do not incorporate sustainability elements, parameters or metrics that are necessary. FGP1 built an analogy on the flowing water by arguing that

entropy is gained as the water cascaded and is lost as it reticulates upwards. By building on this metaphor, an allusion can be made to knowledge transfer capacity.

The pump analogy by FGP4 also inspired the notion of reverse engineering. This can be further explored by exploring the notions of back casting. One of the discussion points from FGP1 contested that engineers and environmental scientists need to collaborate on solutions for the future. This argument resonates with the efforts of this research in creating transdisciplinary knowledge that draws upon various knowledge domains, practitioners and academics using integrative approaches. Another suggestion was that the roles, responsibilities and skills may migrate between the Industrial Engineer and environmental practitioner (FGP1, FGP5). Joint innovation would also shorten the supply chain and increase the value chain.

The philosophy of sustainability research also emerged in the discussion when FGP6 argued that the framework supports and does not ensure a sustainable solution, since there is no single solution to SCA. This realisation was made in this instance despite the positivist research philosophy adopted in the research design.

Discussion topic 4 invited suggestions on the framework which were previously discussed. These concerned the role of Industrial Engineers within sustainability contexts using the framework being defined with a broader context selection priority or decision support system that the framework can be further developed. Another participant voiced a pump analogy to the framework that demonstrates how water would circulate and interact upwards. Something else for consideration would be a prioritisation or weighting of water according to frequency.

Prioritisation has been used to modify "... the cascading stream and maybe adapt the framework to sort of have a heat map representation. Where the water would erode more parts of the pyramid, it would have a darker shade or a lighter shade as opposed to other methods and practices." FGP 6 mentioned that the framework could provide a step-by-step guide to ensure the operationalisation of the framework. The framework was configured to empower organisations to make the strategic, tactical and organisational knowledge component selection. It is also important to consider that this transdisciplinary artefact requires multiple knowledge domains with industry and academic backing. The result of this suggests strong collaboration between various stakeholders in order to ensure a sustainable competitive advantage.

FGP 3 shared that industry often overlooks synergistic relationships that can exist between the various knowledge components that promote a sustainable competitive advantage. Furthermore, it was also mentioned that the investment in the organisation is often a core determinant for the decisions taken by organisations.

10.5 Synthesised analysis of results

The initial phase of this research, characterised by the Systematic Literature Review (SLR), uncovered a significant "subconscious solution space" within IE that remains largely untapped for environmental sustainability (ES) objectives. While the literature identifies critical overlapping components, such as green supply chain operations, circular economy, and technology management, the overall relationship, in practice, was found not to be formalised. However, the subsequent investigations and the application of the Abstract, Contextualise, and Design (ACD) methodology reveal a shift from this deviation, toward an identifiable harmony between strategies, theories, and practices. This evolution suggests that the integration of IE and ES is not merely an additive process but a

transdisciplinary synthesis where concepts such as Industry 5.0, Lean paradigms, and Systems Thinking converge to form a robust framework for socio-environmental problem-solving.

A critical strength of the designed artefact, as identified by participants, is its ability to demonstrate a cascading effect that aligns with strategic, tactical, and operational business execution levels. By integrating Pareto-Weighted Thematic Analysis with the Design Science Research (DSR) cycles, the research moves beyond high-level abstraction to identify synergetic relationships that are often overlooked in traditional industrial settings. The feedback highlighting the need for a step-by-step guide for operationalisation suggests that while the conceptual harmony is well-defined, the practical rollout requires a structured decision-making path to ensure that sustainability initiatives directly contribute to a sustainable competitive advantage, rather than being viewed as competing interests.

The validation of the Pyramid Water Fountain model through the Confirmatory Focus Group (CFG) yielded a grand mean of 4.5 on a 5-point Likert scale, confirming high consensus regarding the model's relevance and structural integrity. Notably, the assertion that the framework accurately embodies IE knowledge received a unanimous score of 5.0, underscoring the discipline's inherent capacity to serve as a catalyst for sustainable development. Despite the high scores, the contesting of the research problem (scoring 3.8) reflects the complex reality of South African industrial environments, where the lack of a formalised, visible and intuitive association between IE and ES is still felt at an operational level. This tension reinforces the necessity of the proposed framework to bridge the gap between theoretical potential and practical execution.

10.6 Chapter summary

The focus group results resoundingly validate the framework, with a high mean score of 4.8 affirming its capacity to successfully resolve the research problem by bridging the gap between IE and environmental sustainability. Participants commended the intuitive cascading logic of the design, noting that it provides a powerful and practical synthesis of strategies that effectively harmonises diverse theories into a unified transdisciplinary system. Ultimately, the framework fosters a synergetic environment where engineers and scientists can innovate together, providing a robust roadmap for organisations to facilitate a lasting sustainable competitive advantage.

Chapter 11

Discussion

11 Discussion

This discussion chapter joins an academic conversation from the SLR by positioning the results and grounding them with the SLR, interviews and CFG.

11.1 Introduction

This chapter serves as the analytical core of the research, synthesizing the empirical findings from the Systematic Literature Review (SLR), the qualitative interview phase — involving twenty-four industry experts and academics — and the Creative Focus Group (CFG). The objective is to triangulate these data sources to address the central research problem. By positioning these findings within the existing body of knowledge, this discussion articulates a shift from traditional efficiency-centric engineering to a sustainability lens approach. This transition is framed through the lens of the Natural-Resource-Based View (NRBV) and the Dynamic Capabilities framework, ultimately validating the proposed IE Pyramid Water Fountain model as a viable transdisciplinary artefact.

11.2 SLR

11.2.1 The literature between IE and ES

The SLR confirmed that there is a lack of formalisation between the IE and ES domains in academic discourse. The IISE Body of Knowledge (BOK), comprising fourteen knowledge areas, does not explicitly incorporate environmental sustainability as a recognised domain ((IISE), 2021a). Similarly, the domain definitions offered by Salvendy (2001) are silent on ecological constraints, despite their growing relevance to operational contexts. This finding directly addresses Sub research Question 1 and fulfils Research Objective 1 by categorising IE and ES knowledge from the literature. What is perhaps of more interest is that neither of the two famous IE taxonomy models speak to environmental sustainability, explicitly. This is a deficiency that IEs have not formally addressed, and it is the basis of this research to explore (Darwish, 2018). Bailey and Barley (2005) posited that the IE profession has, over time, moved away from organisation-focused, integrated systems thinking. This critique resonates with the SLR findings, where engineering tools are applied narrowly within specific industrial contexts rather than in service of systemic environmental solutions. Buzacott (1984) similarly argued that IE lacks cohesiveness; this is a critique this research contests by demonstrating the integrative potential of the discipline when repositioned through a transdisciplinary lens.

A core responsibility of the Engineering Council of South Africa (ECSA) is to regulate engineering activities in accordance with the Engineering Profession Act of 2000 (RSA, 2000). Under Act No. 46, registered persons must practise sustainable development to protect and preserve the environment. A shortcoming is that there is no specific mandate on solutions to address this within the IE domain (Roopa *et al.*, 2024). This institutional gap reinforces the relevance of this research, which seeks to provide exactly that: a structured, knowledge integrated pathway for IE practitioners to operationalise environmental stewardship.

The geographical charting of SLR results reveals that none of the twenty-four papers selected could be affiliated with the African continent. East Asia and the Americas dominate the literature base. This absence is itself a significant finding: it confirms the empirical void that South African IE research can and should fill, a point corroborated by the Scimago rankings, which position South Africa as the highest ranked African country in IE research output with an above average citations per document ratio.

11.2.2 Subconscious solution space

The SLR revealed that a subconscious solution space exists within the IE discipline: a repertoire of theories, strategies, methods and practices that are applicable to environmental problems even though they were not originally formulated with that intent. The Pareto weighted thematic analysis (PWTA) identified Lean and Green integration, Circular Economy and Technology Management as the three most prominently overlapping knowledge components across the IE and ES domains. Approximately 80% of the existing literature engages with a narrow 20% of IE tools, primarily Lean Six Sigma (LSS) and its variants, suggesting that the broader potential of the IE discipline, including enterprise design, systems engineering and ergonomics, remains underutilised in environmental sustainability research (Garza-Reyes, 2015).

Lean thinking, with its foundational orientation toward waste elimination, maps naturally onto the seven categories of green waste identified by Zokaei *et al.* (2013): energy, water, materials, emissions, biodiversity, land use and air quality. When applied with an environmental lens, Lean methods enable organisations to simultaneously reduce operational inefficiencies and environmental burdens, aligning with the pollution prevention strategy within the NRBV from Hart (1995). Similarly, Farias *et al.* (2019) document the complementarity between Lean Six Sigma and environmental performance practices, including Environmental Management Systems (EMS), Life Cycle Assessment (LCA), and Design for the Environment (DFE).

The cumulative year distribution of the SLR papers reveals a sharp increase in publications in 2020 and 2021, reflecting the growing scholarly interest in IE-ES integration in the wake of intensified climate commitments and the mainstreaming of the 17 SDGs (Hák *et al.*, 2018). This temporal pattern confirms that the intersection of IE and ES is not a peripheral research concern but an accelerating frontier, one that South African scholarship is well positioned to shape, given the country's unique developmental context (Ndoricimpa, 2017).

11.2.3 Transdisciplinarity as a bridging mechanism

The SLR revealed that most existing research at the IE-ES intersection adopts a disciplinary, or so much as multidisciplinary, orientation. Very few studies demonstrated genuine transdisciplinary co-production between academic researchers and non-academic practitioners, a finding consistent with the observation from Shrivastava *et al.* (2013): that TD frameworks in sustainable enterprise research remain fragmented. This gap is significant, because as Sakao and Brambila-Macias (2018) argued, environmental sustainability research is inherently transdisciplinary in character, given the complex, systemic and non-linear nature of ecological problems. A disciplinary response to a transdisciplinary challenge is, by definition, limited in scope and impact. In line with the work of Darian-Smith and McCarty (2016) and the International Centre for Transdisciplinary Research (CIRET), the SLR findings confirm that complex and wicked problems, of which IE-ES integration is a prime example, require research approaches that transcend disciplinary silos and create shared lexicons for problem-solving (Monat & Gannon, 2015). The ACD methodology designed in Stage 3 of this research responds directly to this methodological deficit, providing a structured process for transdisciplinary artefact creation, which draws on both the academic literature and practitioner insight from Stage 2.

11.3 Interviews

11.3.1 Transdisciplinary knowledge from industry and academia

The qualitative interview phase engaged twenty-four participants (P1 to P24) across a range of South African industries, including academia, logistics and supply chain management, consulting, energy, manufacturing and entrepreneurship. This purposive snowball sample, guided by saturation principles (Vasileiou *et al.*, 2018), produced transdisciplinary knowledge precisely because it brought together the complementary epistemic perspectives of academic researchers and operational practitioners. The industry representation demonstrates that the most dominant sector was academia, followed by logistics and supply chain management, and then consulting — creating the type of melting pot of diverse knowledge that characterises TD knowledge co-production (Polk, 2015). The Sankey diagram of interview code interactions confirms that the code for IE motivation for environmental sustainability houses the most overlap with other codes and is the most intertwined in the dataset. This is a significant finding because it demonstrates that participants not only recognised the applicability of IE to environmental challenges but viewed this relationship as a core professional motivation rather than a peripheral compliance concern. Industrial engineers are more accountable for environmental degradation despite operational gains created in organisations, given their ability to seek productivity improvements that can be directly translated into environmental performance (Darwish, 2018; Hoque *et al.*, 2018).

11.3.2 Strategy, greenwashing and the embedded sustainability imperative

A recurring and emphatic theme from the interviews was the need for strategic alignment in sustainability initiatives. As articulated by P2, a strategy is about "... understanding what is not known and then understanding that things can change and no longer become true". Strategies need to be symbiotic and cross cutting (P12, P20), and any sustainable strategy needs to be part of the overarching organisational strategy rather than a standalone addition (P4). This reflects the Sensing phase of the Dynamic Capabilities framework (Teece *et al.*, 1997), in which an organisation must scan the environment for emerging threats and opportunities as a prerequisite for sustained competitive advantage.

The dangers of green washing and social washing were cited by P4 and P5 as significant strategic risks. If sustainability initiatives are not embedded within the core organisational strategy, they risk becoming superficial add-ons that fail under economic pressure. This resonates with the broader literature, where de Freitas Netto *et al.* (2020) documented the proliferation of sustainability claims decoupled from operational reality, and Rizzi *et al.* (2020) specifically cautioned against social washing as an erosion of institutional trust. For South African organisations, where regulatory scrutiny and reputational risk are acute, the cost of inauthentic sustainability claims is particularly significant (Piñeiro-Chousa *et al.*, 2017). It also needs to make financial sense for an organisation to even consider the strategy one wishes to employ (P4), introducing a pragmatic qualifier that the IE discipline is ideally positioned to address through quantitative optimisation and cost benefit analysis.

It is also worth mentioning that with IE, we are all systems thinkers (P11). This involves the use of systems engineering principles. According to INCOSE (2023), systems engineering can be seen to involve a transdisciplinary and integrative approach. By derivation, this further argues that the IE discipline could create transdisciplinary solutions to systemic issues (Roopa *et al.*, 2024). The concept of transdisciplinary frameworks such as the rendition from Darian-Smith and McCarty (2016) offers a means of fostering

inclusive, productive and relevance-informed scholarship; and the IE discipline is a natural host for this approach.

11.3.3 Knowledge components: strategies, theories, methods and practices

Many, if not all, of the knowledge components identified from the interviews position themselves with conversion capabilities that could ensure they promote environmental sustainability (P17). Participants 9 and 12 believed that there is a unique opportunity to rephrase the findings of this study, modify the lexicon behind common IE knowledge components and reorient them towards environmental transitions and sustainable considerations. This observation aligns with the categorisation framework of Schlüter *et al.* (2023), who argued that concepts, methods, practices and principles collectively help us understand and act on the world, and that their contextualisation determines their practical impact.

Green Supply Chain Management (GSCM) emerged as a prominent knowledge component from both the SLR and interview phases. In supply chain contexts, supplier selection involves a complex set of decisions, which has led to numerous scholars exploring the topic (Yildiz & Yayla, 2015). The careful selection of suppliers enforces a more sustainable supply chain that improves environmental performance in organisations. Participants corroborated this by discussing the inclusion of environmental performance criteria in procurement decisions, consistent with the Product Stewardship stage of NRBV, which requires extending environmental oversight across the full value chain. The work of Bag *et al.* (2023) on digital supply chains in South Africa provides empirical grounding for this integrative approach.

Circular Economy (CE) was consistently identified as a high impact knowledge component at the IE / ES intersection. CE was pioneered by British economists as an economic development model of resource recycling (Pearce & Turner, 1989; Wang *et al.*, 2024). CE enhances competitiveness through resource efficiency (Garcia-Muiña *et al.*, 2018). Ultimately, there is less waste in the linear economy where equipment life cycles are extended so as to build more robust business models. Garcia-Muiña *et al.* (2018) found that CE adoption is positively associated with firm competitiveness, particularly in resource-constrained environments. This is a finding directly applicable to the South African context, where water and energy scarcity impose binding constraints on operational viability.

Lean and Green emerged as the most extensively cited integrative paradigm across the SLR and interview data. The complementarity between Lean Six Sigma and environmental performance has been well established (Garza-Reyes, 2015; Machingura *et al.*, 2024b). Lean principles, focused on waste elimination, naturally extend to the elimination of green wastes (Zokaei *et al.*, 2017). This suggests that Lean methods, when reoriented through an environmental lens, constitute a practical bridge between IE operational excellence and ES objectives. The PWTa confirmed that Lean and Green commanded the highest combined code density across both the SLR and interview datasets.

Systems Thinking featured prominently as both a strategic approach and a design logic underpinning the IE Pyramid Water Fountain model. Sustainability challenges are messy and non-linear (Monat & Gannon, 2015), and systems thinking provides a means of navigating this complexity by revealing causal relationships across organisational levels. The IE discipline has long been associated with systems engineering, and the close

association between these two fields further substantiates the argument that IE is well positioned to generate transdisciplinary solutions to systemic challenges (Parnell *et al.*, 2022).

Industry 4.0 and Technology Management were cited as important enabling platforms for the IE /ES integration. Digital technologies, including the Internet of Things (IoT), artificial intelligence (AI), blockchain, Big Data analytics and digital twins, reduce information asymmetry in supply chains, making invisible environmental costs both visible and manageable (Bag *et al.*, 2023). Mangaroo-Pillay *et al.* (2023) advanced the concept of Digital Ubuntu as a South African adaptation of Industry 4.0 principles: an approach that integrates communal knowledge sharing values with digital technologies to produce culturally grounded sustainability solutions. The participant example of using 3D printing to produce parts for sunset products (P20) demonstrates the potential for these technologies to simultaneously reduce environmental burden and warehousing costs.

11.3.4 Waste monetisation and the value reframing of sustainability

A significant insight from the qualitative findings is the reframing of sustainability from a cost centre to a value driver. This is a crucial distinction in the South African context, where many firms operate under severe financial constraints. P22 discussed the monetisation of waste streams, and P24 provided a vivid example: a food manufacturing organisation repurposed its process byproducts by selling them to new customers, creating new revenue streams while simultaneously reducing landfill burden. This instantiates the Circular Economy principle of waste as resource and embodies the pollution prevention strategy NRBV, where doing more with less becomes a source of competitive advantage.

For a strategy to become successful, appropriately selected Key Performance Indicators (KPIs) must be tied to a specific strategy (P24). The IE discipline's expertise in measurement system analysis and performance optimisation positions it well to address this imperative; we cannot manage what we cannot measure. Poor metering systems and products not being designed in a sustainable way were cited as structural barriers to sustainability improvement (P3, P15). Smart metering technology and Design for the Environment (DFE) should always be considered, especially in organisations with critical quality control points (Allenby, 1999). Companies can face reputational damage by being transparent about their carbon footprint (P19); companies will therefore need to adopt a culture of owning their carbon footprint and being transparent in their reporting. This paradox aligns with broader global tensions between short-term reputational costs of disclosure and the long-term strategic benefits of genuine sustainability leadership (Piñeiro-Chousa *et al.*, 2017).

For the industrial engineering profession, practical implementation pathways for waste monetisation are also worth consideration. One such instance could draw inspiration from Edirisinghe *et al.* (2024), those who explore genetic algorithm optimisation models that ensure material recovery.

Good maintenance practices in operations can create sustainability opportunities (P22, P24). The knowledge supply chain model of Du Preez and Louw (2007) provides a useful lens for interpreting these practitioner insights. The participants' applied sustainability knowledge represents exactly the tacit, experiential knowledge residing in the competitive stage of the knowledge supply chain: knowledge generated through doing and held within organisational routines. The research design of this study, which deliberately extracted

and formalised this tacit knowledge through structured interviews and thematic analysis, mirrors the Externalisation quadrant of SECI model from Nonaka and Nishiguchi (2001), converting implicit know how into explicit, transferable knowledge components incorporated into the IE Pyramid Water Fountain model.

11.4 Use Case Analysis

11.4.1 Sensing: identifying opportunities and threats

The Use Case Analysis (UCA) applied eight real world cases to assess the capacity of IE knowledge to address environmental sustainability challenges in South African and African contexts, structured around the Sensing, Seizing and Transforming framework of Dynamic Capabilities (Teece *et al.*, 1997). In the Sensing phase, IE tools enabled organisations to perceive environmental threats and opportunities that would otherwise remain invisible. UC1b used simulation based forecasting to sense hydraulic capacity strain driven by population growth, a critical infrastructure challenge in South Africa where rapid urbanisation has placed extreme pressure on water and sanitation systems (Chirisa, 2008). UC2b performed gap analysis on current waste management legislation to identify prominent weaknesses in Mpumalanga's governance framework. UC4b established an as-is baseline by sensing current costs and carbon emissions. These use cases collectively demonstrate that IE's sensing capability, when extended through an environmental lens, can directly operationalise the first stages of NRBV by making biophysical constraints legible to organisational decision makers.

11.4.2 Seizing: mobilising resources to capture value

Once opportunities are sensed, the Seizing phase involves mobilising resources to address them. UC3b demonstrated this by using a hybrid Fuzzy TOPSIS multi criteria decision model to select sustainability aligned maintenance software suppliers, translating environmental aspirations into operationally concrete procurement choices. This responds to the interview finding that sustainability strategies must be tied to measurable KPIs (P24), providing a quantitative basis for supplier selection that incorporates environmental performance alongside cost and quality criteria. UC1b seized the opportunity for resource recovery by integrating Lean Six Sigma with Circular Economy principles in wastewater treatment, using the DMAIC cycle to systematically reduce resource intensity. UC3a used QFD-based mapping to translate sustainable value requirements into engineering design specifications, while UC1a proposed an optimised network design for a novel lease and sell business model. These applications illustrate the Seizing capacity of IE knowledge when deliberately aligned with sustainability objectives.

11.4.3 Transforming: reconfiguring systems and culture

The Transforming phase involves systemic realignment to sustain long term renewal. UC2a proposed the adoption of ten digital technologies, including AI, blockchain and the Internet of Things, to accelerate Africa's circular plastic transition, representing the Sustainable Development strategy of the NRBV where radical innovation redefines the relationship between industrial production and natural systems (De Stefano *et al.*, 2016; Hart, 1995). UC2b addressed industrial symbiosis in Mpumalanga, proposing systemic transitions from linear take-make-dispose models to circular, regenerative systems. UC1b ensured transformation by creating standard operating procedures (SOPs) and incentive programmes to embed sustainability into daily operations, while UC4a emphasised leveraging digitalisation to transform traditional supply chain processes and to cultivate an organisational culture that embraces digital change.

Four of the eight use cases produced quantified improvements: energy savings in UC1b, minor GHG emissions reductions in UC2b, a 20% GHG reduction in UC4b, and over 90% material reduction in UC3a. Collectively, this demonstrates the ability to address energy savings, GHG emissions and material consumption if combined holistically using the IE Pyramid Water Fountain model. Given that the TD artefact summates the various knowledge components, it suggests that these sustainability metrics can also be addressed in real world contexts, simultaneously. These outcomes respond to the practitioner challenge from P4, who argued that sustainability must be financially and operationally demonstrable; the use cases provide exactly this form of evidence.

11.5 The IE Pyramid Water Fountain Model

11.5.1 Design logic and theoretical alignment

The IE Pyramid Water Fountain model, designed using the ACD methodology, represents the primary intellectual and practical contribution of this research. The cascading effect from the framework refers to the flow of water along dedicated sides of the Pyramid Water Fountain which continuously recirculates upwards and back down. The flow of water is never consistent, and so opportunities emerge to have organisations follow a new or slightly varied approach to achieve a sustainable competitive advantage. This design logic is both metaphorically resonant and theoretically grounded: the cascade represents the sequential, top down application of knowledge from strategic intent to operational execution, while the reticulation represents the feedback and continuous improvement cycles that Nonaka and Takeuchi (1995) identified as essential to sustained knowledge creation.

The model operationalises transdisciplinary integration by aligning strategies, theories, methods and practices along three business execution levels: strategic, tactical and operational. This three-level alignment responds to the practitioner insight from P4 that sustainability strategies must be embedded within — not appended to — the organisational strategy. The PWTA filtering mechanism ensures that the knowledge components incorporated into the framework are grounded in the most robustly evidenced intersection of IE and ES, satisfying the rigour requirements for Design Science Research (Hevner *et al.*, 2010). The DSR knowledge contribution framework of Gregor and Hevner (2013) positions this artefact as an Exaptation: extending known IE solutions to the new problem domain of environmental sustainability and sustainable competitive advantage in South Africa.

The framework advances the debate on IE / ES integration by operationalising TD alignment consistent with Lang *et al.* (2012) and Hadorn *et al.* (2008), who argued that sustainability challenges cannot be resolved within disciplinary silos. The prominence of Lean and Green within the PWTA supports earlier work arguing for convergence between efficiency driven IE paradigms and environmental performance (Garza-Reyes, 2015; Machingura *et al.*, 2024b). However, this study goes beyond demonstrating compatibility; it shows that Lean and Green acts as a theoretical bridge linking high level sustainability strategies, such as CE and SDGs, to execution level practices, like VSM, 5S, and 3R to 12R principles, that organisations can immediately deploy.

Theory classified in the artefact also moves into applied theory. For example, decarbonisation was found to connect with 88 distinct theories in research by Sovacool *et al.* (2023) across eight families of perspectives. This included sociotechnical transitions, innovation and diffusion, organisational behaviour and governance. The same

can be said for factory design which is applied theory. More broadly, Friedman (2003) discuss design theory generally, arguing that design theory must draw from supporting theories rather than independent sciences. Complementary to this, Spillers and Newsome (1988) characterise design theory as a metatheory, one which is a theory about theories. Nonetheless, the current categorisation creates a cohesive application of various solution spaces for SCA.

11.5.2 NRBV, RBV and the competitive logic of the framework

The IE Pyramid Water Fountain model is theoretically anchored in (Hart & Dowell, 2011) NRBV, which posits that firms achieve sustained competitive advantage by developing capabilities aligned with ecological constraints across three stages: Pollution Prevention, Product Stewardship and Sustainable Development. Each stage is evidenced in this research. Pollution Prevention corresponds to the Lean and Green paradigm: reducing waste and energy through IE tools creates capabilities that competitors find difficult to replicate (Hart & Dowell, 2011). Product Stewardship is evidenced in UC3a, where life cycle design reduced material consumption by over 90%, and in the interview evidence around DFE and smart metering, requiring the extension of environmental oversight across the full value chain. Sustainable Development is represented by UC2a's digital circular plastics economy proposal, where radical innovation redefines firm value creation in relation to natural systems.

Within the VRIO framework, the IE Pyramid Water Fountain model is Valuable because it enables organisations to respond to growing sustainability demands in ways that simultaneously reduce costs and open new markets. It is Rare because no comparable integrative framework currently draws on the full breadth of IE knowledge and explicitly aligns it to ES and SCA logic. It is Inimitable because its value derives from a socially complex, causally ambiguous process of transdisciplinary co production: knowledge that is deeply tacit and inherently difficult for competitors to replicate (Barney, 1995; Hart, 1995). Kraaijenbrink *et al.* (2010) acknowledged the VRIO limitation regarding its static nature. However, the dynamic reticulation design of the fountain model specifically addresses this critique by ensuring continuous knowledge renewal. Finally, the framework's value is contingent on Organisation: the firm's capacity to deploy it through appropriate structures, routines and leadership —, a condition that underscores the skills acquisition challenge raised in the CFG.

The debate between the NRBV and Dynamic Capabilities finds its resolution in the IE Pyramid Water Fountain model. While Dynamic Capabilities achieves incremental or evolutionary gains within existing market structures (Eisenhardt & Martin, 2017), NRBV is designed for discontinuous change required by the sustainability transition (De Stefano *et al.*, 2016). DC theory does not intuitively solve for the rising cost of raw materials or energy volatility (Shuen *et al.*, 2014). In contrast, NRBV prioritises product stewardship by considering the entire product life cycle: a foresight approach that reduces resource dependency and builds resilience (Lewis, 2017). Given that environmental sustainability is a specific knowledge domain within the scope of this research, NRBV provides the more direct strategic logic, while DC provides the process mechanism for adaptive execution.

11.5.3 Biomimicry and the nature-inspired design logic

Part of the ACD methodology is inspired by a biomimicry approach. Nature has been fine tuning its systems for over three billion years, creating a massive repository of blueprints that humanity is only just beginning to decode (Benyus, 1997). The water fountain

metaphor is not merely aesthetic; it draws on the ecological principles of continuous circulation, adaptive flow and ecosystem interdependence that this research argues should characterise the relationship between IE and ES in South African organisations. Kennedy and Marting (2016) argued that biomimicry streamlines the front end of innovation, allowing researchers to bypass trial and error by consulting solutions already vetted by evolution. By emulating nature's genius in the design logic of the framework, the ACD methodology operationalises the biomimetic insight that sustainable competitive advantage is most durable when it mirrors the resilience, circularity and adaptive efficiency of natural systems.

11.6 Confirmatory Focus Group

The Confirmatory Focus Group (CFG) convened six expert participants via Microsoft Teams to evaluate the IE Pyramid Water Fountain model and generate qualitative insights to enrich its theoretical interpretation. A grand mean of 4.5 on a five-point Likert scale, alongside an average standard deviation of 0.5, is indicative of high acceptance and strong consensus on the survey statements used to evaluate the TD artefact. The unanimous score of 5.0 on the statement affirming that the framework accurately embodies IE knowledge is particularly significant: underscoring the discipline's inherent capacity to serve as a catalyst for a sustainable competitive advantage and confirming that the PWTA driven integration was successful.

One of the most productive discussions in the CFG centred on the cascading and reticulating design logic of the framework. FGP2 affirmed the design as practical and understandable. A question was posed by FGP6 asking for clarity on whether the framework considers the upward influence of water thus symbolising the feedback of operational learning back to strategic orientation. FGP4 built on this by proposing a pump mechanism for the framework that can resemble methodological steps and strategic intent behind new sustainability initiatives, using carbon footprinting as an example that could be reverse engineered back to SDG alignment. FGP1 introduced the entropy analogy, arguing that knowledge, such as water, loses energy as it cascades downward and must be actively replenished through feedback mechanisms and continuous learning. This entropy analogy resonates with the knowledge supply chain model of Du Preez and Louw (2007), which recognises that knowledge can become obsolete as it traverses the public, private and user domains. It also aligns with the knowledge spiral of Nonaka and Takeuchi (1995), where knowledge is continuously recreated through cycles of Socialisation, Externalisation, Combination and Internalisation.

The reticulation mechanism of the water fountain, representing these feedback loops, ensures that the framework is not a static prescriptive tool but a living, adaptive instrument that organisations can recalibrate as their sustainability journey matures. FGP5 observed that the framework interpretation has duality in its application, noting that FGP1 believed the research was bringing sustainability into IE, while FGP5 saw it the other way: bringing IE into sustainability. It was further suggested that the framework should achieve both, which corroborates the notion of this research having produced a genuinely transdisciplinary artefact.

FGP1 articulated that one of the biggest challenges with the topic is that the development sees engineering and conservation as siloed facets that weigh industry against the environment. This argument was further stressed through the observation that engineers and environmental scientists need to innovate solutions for the future with each other, and not for each other: a principle that encapsulates the transdisciplinary ethos of this

research and resonates with the NRBV's product stewardship requirement for stakeholder integration. FGP6 mentioned that the skills acquisition process for organisations may be worth exploring further, given that effective deployment of the framework requires a workforce literate in both IE and ES concepts. FGP3 shared that industry often overlooks synergistic relationships among the various knowledge components that promote a sustainable competitive advantage.

11.7 Industrial Ecology and Industrial Engineering

Given the environmental sustainability focused approach of this study from an Industrial Engineering perspective, the field of Industrial Ecology cannot go unnoticed. The relationship between industrial ecology and industrial engineering is one of convergent aims pursued through historically distinct methodological traditions, and this convergence is central to understanding why the two fields have become increasingly intertwined in contemporary sustainability-oriented research. Industrial ecology was formally inaugurated by Frosch and Gallopoulos (1989), who proposed that industrial systems be reconfigured as artificial ecosystems in which the use of energy and materials is optimised, waste and pollution are minimised, and there is an economically viable role for every product of a given process. This framing positioned industrial ecology as an inherently systems-level, cross-organisational discipline, concerned with material and energy flows that traverse firm boundaries, a concern later formalised through the study of industrial symbiosis, in which geographically proximate firms exchange by-products, energy, and water within mutually beneficial exchange networks (Chertow, 2000). Industrial engineering, by contrast, has historically operated at the level of the individual firm or process, applying optimisation, systems design, and continuous improvement techniques to enhance efficiency, throughput, and quality within a bounded operational system. Read together, the analytical distance between these two traditions is narrower than their separate disciplinary histories imply. This is because industrial ecology supplies the systems-level, ecosystem-oriented lens through which resource flows across organisational boundaries can be understood and evaluated, while industrial engineering supplies the process-level methodological solution space, systems engineering, optimisation, and design methods, through which those flows can actually be redesigned, implemented, and sustained within and between operating organisations (Haskins, 2007).

This complementarity is not without tension, and the tension itself is instructive. Ehrenfeld (2004) has questioned whether industrial ecology constitutes a genuinely distinct scientific field or functions primarily as an organising metaphor, formalising biological ecosystem theory, in a manner which reframes how engineers and managers think about industrial systems without necessarily supplying a novel methodological apparatus or notion of its own. Read in this light, industrial engineering can be understood as supplying much of the methodological apparatus that industrial ecology's ecosystem metaphor implicitly calls for. It can achieve this without established industrial engineering techniques for process mapping, flow optimisation, and systems design; the conceptual vision of industrial ecology, an economically viable role for every by-product within a closed-loop industrial ecosystem, and this would remain aspirational rather than operational. Industrial ecology and industrial engineering are therefore best understood not as competing or substitutable disciplines but as mutually constitutive.

11.8 Synthesis and implications

The integrative and collaborative nature of TD derives systemic, ethical and context specific solutions that strengthen South Africa's sustainable competitiveness. This has been outlined by the taxonomy associations in Chapter 2, as well as by empirical and

conceptual cases in the UCA and CFG. The Sołoducho-Pelc and Sulich (2020) SCA taxonomy identifies innovations, environmental change, people and leadership, strategy, culture and value creation, market orientation and resource capabilities as the core dimensions of sustainable competitive advantage, dimensions that map directly onto the strategic, tactical and operational levels of the IE Pyramid Water Fountain model. For South African organisations to decouple growth from resource depletion, they must adopt nature-inspired analogies and biomimetic perspectives within their innovation pipelines (Benyus, 1997; Kennedy & Marting, 2016). South Africa has a high resource intensity and environmental risk, which can impact firm resilience and market position (Kennedy *et al.*, 2015). By applying IE thinking with a sustainability lens, environmental practices can be improved to reduce waste and strengthen the competitive advantage of an organisation.

Thekkoote (2022) demonstrated that Lean and Green integration in South African SMEs improves operational performance, a finding that validates the framework's focus on these two domains as entry level knowledge components for organisations at earlier stages of the sustainability journey. The IE Pyramid Water Fountain model provides a roadmap that is both locally relevant and globally applicable, especially important for emerging economies such as South Africa (Roopa, 2024).

11.9 Chapter summary

This chapter provides a comprehensive synthesis and critical discussion of the empirical results harvested across the four iterative stages of this research. The SLR underscored a persistent disciplinary chasm between IE and ES, yet simultaneously illuminated a nascent subconscious solution space where knowledge components such as Lean and Green integration, the Circular Economy, and Technology Management naturally converge. These foundations were further solidified during the qualitative interview phase, which generated transdisciplinary insights from twenty-four South African practitioners and academics. This grounded practical themes such as waste monetisation, smart metering, and Design for Environment within the core IE pillars of measurement and optimisation.

The Use Case Analysis subsequently demonstrated the framework's versatility across diverse sectors, validating the inherent Sensing, Seizing, and Transforming capacities of IE knowledge within a Dynamic Capabilities framework to yield quantified sustainability outcomes. Finally, the Collaborative Focus Group offered a resounding validation of the artefact, yielding a grand mean of 4.5. These qualitative discussions further nuanced the model through the pump analogy and entropy metaphors, while advocating for a context-specific South African adaptation. Ultimately, these findings harmonise with the existing literature and delineate knowledge components into a robust, three-tiered business execution model comprising strategic, tactical, and operational levels. This synthesis establishes the necessary groundwork for the final chapter, which details the conclusions, novelty, and strategic recommendations emanating from this study.

Chapter 12

Conclusions, novelty, limitations and recommendations

12 Conclusions, novelty, limitations and recommendations

12.1 Concluding remarks

The modern industrial landscape in South Africa is defined by a dual mandate: the drive for heightened productivity and the urgent requirement for environmental stewardship. This research addressed this challenge by seeking to integrate Industrial Engineering (IE) and environmental sustainability (ES) knowledge to achieve a sustainable competitive advantage (SCA) in South Africa using transdisciplinary knowledge creation (**Research Aim**). Central to this investigation was a fundamental inquiry into how IE knowledge can be integrated with ES to ensure a sustainable competitive advantage in South Africa (**Central Research Question**). By bridging these often-siloed domains, the study provides a systemic path for organisations to navigate the "wicked" complexities of the modern industrial environment. Furthermore, it remedies the problem statement by establishing a formal, visible and intuitive classification of IE and ES within TD contexts.

To establish a theoretical foundation, the study first interrogated the relationship between IE knowledge and environmental sustainability knowledge (**Sub-research Question 1**). Through a systematic literature review and applied thematic analysis (ATA), the study successfully identified and categorised IE and environmental sustainability knowledge from literature (**Research Objective 1**). The findings revealed that while a subconscious solution space exists, the two fields remain largely disjointed in dominant academic discourse. However, by identifying overlapping themes such as the circular economy, green innovation, and technology management, the research established a conceptual harmony that serves as the baseline for further transdisciplinary integration.

Expanding beyond the literature, the research investigated which knowledge components can be retrieved from industry and academia to achieve a sustainable competitive advantage in South Africa (**Sub-research Question 2**). This facilitated the objective to identify IE and environmental sustainability knowledge applied in South Africa that ensures a sustainable competitive advantage (**Research Objective 2**). The empirical data, synthesised from practitioners and managers, highlighted that the successful operationalisation of sustainability requires a transition from abstract concepts to specific IE-driven practices — such as Industry 5.0 and Lean paradigms — that align with local socio-economic realities and national policy frameworks.

Recognising the limitations of traditional, mono-disciplinary approaches to complex problems, the study questioned what type of design methodology can be created for transdisciplinary problem solving (**Sub-research Question 3**). This led to the creation of a design methodology for transdisciplinary problem solving in South Africa (**Research Objective 3**), specifically utilizing the Abstract, Contextualise, and Design (ACD) methodology. This methodology allows for the synthesis of disparate knowledge types, enabling engineers to co-design solutions that address systemic sustainability challenges while maintaining technical and economic viability.

The culmination of this research addressed how a framework can be designed and tested to ensure that IE knowledge facilitates a sustainable competitive advantage for South Africa (**Sub-research Question 4**). The study sought to design a framework that integrates the preceding IE and environmental sustainability knowledge created (**Research Objective 4**), resulting in the development of the Pyramid Water Fountain Model. Finally, through a confirmatory focus group and use case analysis, the research evaluated the ability of the framework to facilitate a sustainable competitive advantage in South Africa (**Research Objective 5**). The high consensus achieved during this validation

phase reinforces the assertion that a transdisciplinary approach provides a robust, systemic narrative for achieving enduring industrial and environmental excellence in South Africa.

Upon reflection, each stage of this research presents a contribution discussed in the following subsection.

12.2 Novelty

This research is the first of its kind to propose transdisciplinary knowledge that is comprised of integrated IE and ES knowledge. This study redefines IE as the main driver of Environmental Sustainability (ES) through a transdisciplinary synthesis. The study goes beyond occasional literature to create a rigorous TD framework for synergy between various domains by combining an SLR, 24 expert interviews, Pareto-weighted thematic analysis, a crafted TD methodology and an intuitive design approach.

The first research paper explains how the confluence of IE and ES provides an SCA, whereas prior research frequently regards them as competing interests. The IISE Body of Knowledge's classification of overlapping knowledge components speaks to Green Supply Chain, Circular Economy and Technology Management.

The second publication finds harmony between strategies, theories, methods and practices. This contrasts with the novelty in the SLR, which argued a lack of formalisation between IE and ES. The search for harmony here suggests more integrative knowledge components that ensure an SCA. Aspects such as Industry 5.0, Lean, and Systems Thinking emerged.

A new TD methodology (ACD) is created and applied to design the intended artefact. To creatively integrate the IE and ES knowledge from the SLR and interview, the novel Pareto-weighted Thematic Analysis is employed. Holistically, this gives practitioners a methodical approach for concurrent ecological and operational improvements. The main contribution is the creation of a framework that is both locally relevant and globally applicable, especially important for emerging countries such as South Africa. The UCA is predominantly targeted to the South African and African context, suggesting and showcasing a mechanism to evaluate the TD artefact for continental or domestic performance against sustainability objectives. By mapping these transdisciplinary touchpoints illustrated in the IE Pyramid Water Fountain Model, this research provides a foundational blueprint for engineers to address complex societal challenges. The work is thus able to use IE as a transformative tool for productivity and sustainable transitions in lieu of global and domestic sustainability objectives.

This research demonstrates transdisciplinary synthesis techniques by combining a systematic literature review, 24 expert interviews with South African industrial engineers and environmental practitioners, and Pareto-Weighted Thematic Analysis as an extension of the coding logic established by Braun and Clarke, (2006). It uses these to cascade knowledge components across strategic, tactical and operational business execution levels rather than treating literature and practitioner data as separate evidentiary streams. These techniques feed two design artefacts built using the Abstract, Contextualise and Design methodology: the Lighthouse Model (Chapter 6), which abstracts the physical mechanics of a lighthouse, lens, turntable, base and clock, into 28 consolidated solution fragments for transdisciplinary, foresight-oriented problem-solving aligned with the UN Sustainable Development Goals. It draws directly on the sustainability lighthouse concept introduced by Holmberg and Larsson (2018). In addition, it draws on

the Pyramid Waterfall Fountain Model (Chapter 7), which organises the same knowledge components using a morphological (Zwicky) box structure, the classification method formalised by Zwicky (1969). In doing so, it visualises their cascading strategic-to-operational relationships through alluvial and sunburst diagrams structured around a water analogy, producing the thesis's principal artefact for pursuing a sustainable competitive advantage through integrated industrial engineering and environmental sustainability knowledge.

The selection of DSR-orientated research was motivated in Chapter 3. One of the gains of this is the DSR knowledge contribution framework, which positions the DSR research contribution from a specific project. Figure 36 depicts this framework and the core positioning of this research.

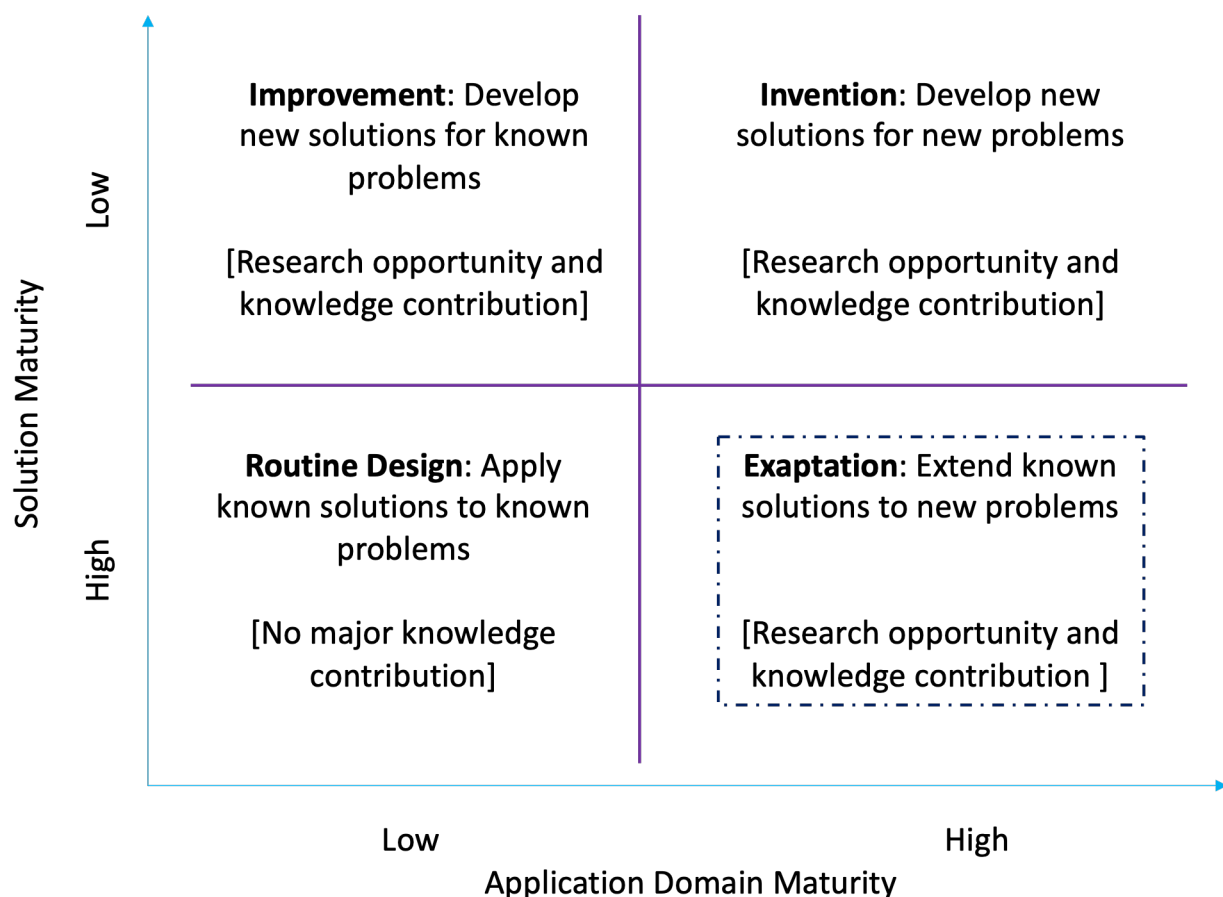


Figure 34 DSR knowledge contribution framework, adapted from Gregor and Hevner (2013:9)

As can be seen, the four classes are segmented according to maturity in terms of the solution maturity and application maturity. Given that this research has embarked on developing a new TD solution, it still uses an existing set of solutions that were harnessed from literature and interviews. For this reason, the solution maturity is high. As for the application domain, the research opportunity makes this applicable to various sectors, since it has TD attributes. For these reasons, the DSR knowledge contribution can be seen as an exaptation that extends known solutions to new problems when trying to develop or maintain a sustainable competitive advantage. This ultimately produces contributions to all knowledge components associated with strategy, theory and practice.

12.3 Limitations and Recommendations

No research functions in isolation; in this way, many opportunities and new questions emerge from this study. One of the first suggestions is to explore integrating more fields of engineering that welcome another sustainability narrative. Such examples include sustainable engineering, chemical engineering and other disciplines that cater for competitiveness and sustainability within organisations.

IE needs to evolve to achieve sustainable competitiveness through the development of Competition Engineering: a new function aimed at addressing future challenges (Gilb, 2005). An exploration on competition or competitive engineering with environmental sustainability may forge another means of mapping sustainable competitive advantage pathways that are transdisciplinary in nature.

Work from Polk (2015) on TD-production can be used to explore the challenges with TD production and how this research responds to these challenges. These avenues include ways in which one captures multiple framings, integrating knowledge diversity and contributing to societal change. Multiple framings can be mapped differently using mono and mixed methods techniques (Saunders *et al.*, 2009). Furthermore, integrating knowledge diversity welcomes country-specific cultural contexts to calibrate artefacts before implementation. Another trajectory to further this research could apply cultural adaptations of the TD artefact, similar to Mangaroo-Pillay *et al.* (2023) who suggest a South African version of Industry 4.0. Perhaps more country-specific cultural adaptations could unlock aspects to increase organisational buy-in and adoption with regard to the interface between ES and culture. Some work has explored the culture-sustainability relation across 57 countries and the role of culture in ES as suggested starting blocks for socio-environmental TD artefact creation (Huang *et al.*, 2024; Soini & Dessein, 2016).

For organisations, alternative adaptations of frameworks have shown to increase the success rate (Butler *et al.*, 2017). Although the ACD methodology was able to aid in the integration of the IE and ES knowledge components to create a TD artefact, efforts could be made to design new or apply existing TD problem-solving methodologies to address SCA. Other examples include TD problem-solving frameworks, combined TD and design thinking and iterative stakeholder looped approaches (Knierim & Callenius, 2018; Ozsoy & Mengüç, 2024; Yeh, 2019). As much as re-applying the same integration of the knowledge components could render a new TD artefact, implying new interaction points, flow and method of execution.

This research and application of DSR has been rendered a theoretical solution tested by means of a use case analysis (Chapter 9). Future work should strive to implement and evaluate the performance or execution of this TD artefact in a real organisational.

Part of the ACD methodology is inspired by a biomimicry approach. By emulating nature's genius, one can further sustainable innovation (Kennedy *et al.*, 2015). One such example of a nature-inspired analogy is from Villar *et al.* (2021). Future research should move this biomimetic idea from analogy to testable industrial-engineering models, by translating protein-biosynthesis principles into production planning, sourcing control, and digital-twin architectures; then checking whether those rules improve throughput, coordination, and disruption resilience in real supply chains. It should also quantify environmental gains directly, especially waste reduction, circularity and emissions, because the broader nature-inspired supply-chain literature has focused mainly on closed-loop systems while industrial symbiosis, circular economy, industrial ecology, and biomimicry remain comparatively underexplored; the evidence found suggests bio-inspired network design

can reduce vulnerability to cascading failures, which makes resilience a concrete bridge to sustainability. This is an initial search, so a deeper pass could surface additional biomimetic and cleaner-production studies that sharpen the recommendation.

The knowledge component integration only considered IE and ES, given the research focus defined in Chapter 1. Opportunities therefore exist to harness knowledge components from similar complementary engineering disciplines. This could entail retrieving knowledge from sustainable engineering, systems engineering since they, too, align with achieving the sustainability narrative but without as much competitiveness.

Another drawback is the limited sample size, and so future work could also extend to different stakeholders in the spirit of TD research. In addition, the TD artefact expected performance and utility could be measured against different industrial engineering sectors. Broader implications can explore professional engineering bodies, curriculum development, and sustainability policy as well. The findings suggest that for South African organisations to decouple growth from resource depletion, they must adopt nature-inspired analogies and biomimetic perspectives within their innovation pipelines. The ACD methodology provides a transdisciplinary bridge that allows IE practitioners to sidestep traditional critiques of industrialisation and instead co-design solutions that meet both local policy mandates and global Sustainable Development Goals (SDGs). Looking forward, the success of this integration within the IE domain paves the way for expanding the framework to include complementary disciplines such as systems engineering and sustainable engineering, further enriching the transdisciplinary narrative of industrial excellence in developing economies.

The integration of Industrial Engineering and Environmental Sustainability is no longer an elective for South African industry; it is a strategic imperative. This research has demonstrated that by utilising transdisciplinary frameworks and modifying the traditional IE lexicon, the discipline can lead the transition toward a regenerative and competitive industrial sector. The IE Pyramid Water Fountain model provides a robust, context-sensitive mechanism for achieving this integration, ensuring that South African engineering remains relevant in a sustainability-conscious global economy. This research motivates TD research by integrating IE and ES for a sustainable competitive advantage. TD offers systemic problem-solving capability to best advance organisational competitiveness and environmental preservation as a sustainable *modus operandi* in all parts of the world. For the academics within this TD environment, their obligation is to pursue sustainable competitive advantage research between disciplinary and transdisciplinary approaches by leveraging non-formalised solution spaces in the literature. The suggestion for practitioners is rather simple, create and implement sustainable solutions that allow for societal progression, environmental conservation and healthy competition in various industries. Together, society can create sustainable solutions for all.

References

References

- (IISE), I.o.I.a.S.E. 2021a. *IISE Body of Knowledge*. <https://www.iise.org/Details.aspx?id=43631>
- Abdallah, K.S. & El-Beheiry, M.M. 2022. A SYSTEM DYNAMICS MODEL ASSESSING THE SUSTAINABILITY OF THE PERFORMANCE OF SUPPLY CHAINS WITH REVERSE FLOW. *International Journal of Industrial Engineering*, 29(4),
- Adolph, J. & Beckmann, M. 2024. Corporate sustainability strategy: From definitional ambiguity toward conceptual clarification. *Business Strategy and the Environment*, 33(5):4708-4729.
- Adzic, G. & Bisset, M. 2012. *Impact Mapping: Making a big impact with software products and projects*. Provoking Thoughts Limited.
- Al-Ghamdi, S., Qureshi, M., Almakayeel, N., Mansour, M. & Abdul Khadar, S. 2023. An approach to attaining sustainability by enhancing the environmental factors that affect the quality of urban life. *South African Journal of Industrial Engineering*, 34(1):42-60.
- Albliwi, S., Antony, J., Lim, S.A.H. & van der Wiele, T. 2014. Critical failure factors of Lean Six Sigma: a systematic literature review. *International Journal of Quality & Reliability Management*, 31(9):1012-1030.
- Alessandro, B., Caterina, C., Marinella, L., Francesco, R. & Alessandro, Z. 2017. Biomimicry thinking: methodological improvements and practical implementation. *Bioinspired, Biomimetic and Nanobiomaterials*, 6(2):87-101.
<https://www.icvirtuallibrary.com/doi/abs/10.1680/jbibn.16.00007> 10.1680/jbibn.16.00007
- Alexander, P., Antony, J., Rodgers, B.J.I.J.o.Q. & Management, R. 2019. Lean Six Sigma for small-and medium-sized manufacturing enterprises: a systematic review.
- Alharahsheh, H.H.a.P., A., 2020. 2020. A review of key paradigms: Positivism VS interpretivism 2(3). *Global Academic Journal of Humanities and Social Sciences*, 2(3):pp.39-43.,
- Alkaraan, F., Elmarzouky, M., Hussainey, K., Venkatesh, V., Shi, Y. & Gulko, N. 2024. Reinforcing green business strategies with Industry 4.0 and governance towards sustainability: Natural-resource-based view and dynamic capability. *Business Strategy and the Environment*, 33(4):3588-3606.
- Allen, J.H., Beaudoin, F., Lloyd-Pool, E. & Sherman, J. 2014. Pathways to sustainability careers: building capacity to solve complex problems. *Sustainability: The Journal of Record*, 7(1):47-53.
- Allenby, B.R. 1999. Industrial ecology and design for environment. *Proceedings First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*:2-8.
- Alsaawi, A. 2014. A Critical Review of Qualitative Interviews. In.
- Alvesson, M. & Sandberg, J.J.A.o.m.r. 2011. Generating research questions through problematization. 36(2):247-271.
- Amaya, N., Bernal-Torres, C.A., Nicolás-Rojas, Y.W. & Pando-Ezcurra, T.T. 2024. Role of internal resources on the competitive advantage building in a knowledge-intensive organisation in an emerging market. *VINE Journal of Information and Knowledge Management Systems*, 54(5):1153-1169.
- Angelstam, P., Andersson, K.R., Annerstedt, M., Axelsson, R., Elbakidze, M., Garrido, P., ... Stjernquist, I. 2013. Solving Problems in Social–Ecological Systems: Definition, Practice and Barriers of Transdisciplinary Research. *Ambio*, 42:254 - 265.

- Anthony, B., Majid, M.A. & Romli, A. 2017. A model for adopting sustainable practices in software based organizations. In. 2017 8th International Conference on Information Technology (ICIT). pp. 26-35.
- Appiah, L.O., Essuman, D., Forson, C.A., Boso, N. & Annan, J. 2025. Green process innovation and financial performance in small and medium-sized enterprises in a developing Country: Role of resource orchestration. *Journal of Business Research*, 189:115210.
- Armitage, A. & Keeble-Allen, D. 2008. Undertaking a structured literature review or structuring a literature review: Tales from the field. In. Proceedings of the 7th European Conference on Research Methodology for Business and Management Studies: ECRM2008, Regent's College, London. p 35.
- Asha, S., Vyshnavi, A., Todi, S. & Akanksha, P. 2023. A study on environmental sustainability-growth, trends and concerns. *International Journal For Multidisciplinary Research*, 5(2):1-6.
- Askalidis, G., Kim, S.J. & Malthouse, E.C. 2017. Understanding and overcoming biases in online review systems. *Decision Support Systems*, 97:23-30.
- Axelsson, R., Ljung, M., Blicharska, M., Frisk, M., Henningsson, M., Mikusiński, G., ... Sjölund, A. 2020. The challenge of transdisciplinary research: A case study of learning by evaluation for sustainable transport infrastructures. *Sustainability*, 12(17):6995.
- Azhar, S., Ahmad, I. & Sein, M.K. 2010. Action research as a proactive research method for construction engineering and management. *Journal of construction engineering and management*, 136(1):87-98.
- Azungah, T. 2018. Qualitative research: deductive and inductive approaches to data analysis. *Qualitative Research Journal*,
- Babbie, E.R. 2020. *The practice of social research*. Cengage Au.
- Bag, S., Wood, L.C., Telukdarie, A. & Venkatesh, V. 2023. Application of Industry 4.0 tools to empower circular economy and achieving sustainability in supply chain operations. *Production planning & control*, 34(10):918-940.
- Bailey, D.E. & Barley, S.R. 2005. Return to work: Toward post-industrial engineering. *IIE Transactions*, 37(8):737-752.
- Baloch, M.A., Danish, Khan, S.U.-D., Ulucak, Z.Ş. & Ahmad, A. 2020. Analyzing the relationship between poverty, income inequality, and CO2 emission in Sub-Saharan African countries. *Science of The Total Environment*, 740:139867.
<https://www.sciencedirect.com/science/article/pii/S0048969720333878>
<https://doi.org/10.1016/j.scitotenv.2020.139867>
- Bardzell, J. & Bardzell, S. 2013. What is" critical" about critical design? In. Proceedings of the SIGCHI conference on human factors in computing systems. pp. 3297-3306.
- Barney, J. 1991. Firm resources and sustained competitive advantage. *Journal of management*, 17(1):99-120.
- Barney, J.B. 1995. Looking inside for competitive advantage. *Academy of Management Perspectives*, 9(4):49-61.
- Barney, J.B., Ketchen Jr, D.J. & Wright, M. 2021. Resource-based theory and the value creation framework. *Journal of management*, 47(7):1936-1955.

- Barton, J.R. & Gutiérrez-Antinopai, F. 2020. Towards a visual typology of sustainability and sustainable development. *Sustainability*, 12(19):7935.
- Baskerville, R. & Wood-Harper, A.T. 1998. Diversity in information systems action research methods. *European Journal of information systems*, 7(2):90-107.
- Belcher, B.M., Rasmussen, K.E., Kemshaw, M.R. & Zornes, D. 2016. Defining and assessing research quality in a transdisciplinary context. *Research Evaluation*, 25:1-17.
- Benyus, J.M. 1997. *Biomimicry: Innovation inspired by nature*. Morrow New York.
- Benzerrouk, Z., Abid, M. & Sekrafi, H. 2021. Pollution haven or halo effect? A comparative analysis of developing and developed countries. *Energy Reports*, 7:4862-4871.
<https://www.sciencedirect.com/science/article/pii/S2352484721005436>
<https://doi.org/10.1016/j.egyr.2021.07.076>
- Bhadra, K., Kamalanabhan, T. & Singh, S.K. 2024. Evolution of dynamic capabilities for business sustainability performance: evidence from the Indian manufacturing sector. *Business Strategy and the Environment*, 33(6):5583-5605.
- Bian, Z., Zhang, Y., Lin, H., Zhu, Y. & Zhang, J. 2025. Integrating sustainability into biologically inspired design: A systematic evaluation model. *Biomimetics*, 10(2):111.
- Bidanda, B. 2022. *Maynard's Industrial and Systems Engineering Handbook*. McGraw Hill Professional.
- Blair, J., Czaja, R.F. & Blair, E.A. 2013. *Designing Surveys: A Guide to Decisions and Procedures*. SAGE Publications.
- Blicharska, M., Smithers, R.J., Kuchler, M., Agrawal, G.K., Gutiérrez, J.M., Hassanali, A., ... Mshinda, H.M. 2017. Steps to overcome the North–South divide in research relevant to climate change policy and practice. *Nature Climate Change*, 7(1):21-27.
- Bose, S. 2020. Evolution of ESG reporting frameworks. *Values at work: Sustainable investing and ESG reporting*:13-33.
- Botha, A.P. 2018. Rapidly arriving futures: future readiness for Industry 4.0. *South African journal of industrial engineering*, 29(3):148-160.
- Bowen, G.A. 2009a. Document analysis as a qualitative research method. *Qualitative research journal*, 9(2):27-40.
- Bowen, S. 2008. Getting it right: Lessons learned in applying a critical artefact approach.
- Bowen, S.J. 2009b. *A critical artefact methodology: Using provocative conceptual designs to foster human-centred innovation*. Sheffield Hallam University (United Kingdom).
- Bracken, L.J., Bulkeley, H.A. & Whitman, G. 2015. Transdisciplinary research: understanding the stakeholder perspective. *Journal of environmental planning and management*, 58(7):1291-1308.
- Brainard, S.G. & Carlin, L. 1997. A longitudinal study of undergraduate women in engineering and science. In. *Proceedings Frontiers in Education 1997 27th Annual Conference. Teaching and Learning in an Era of Change*. pp. 134-143 vol.131.
- Brandt, P., Ernst, A., Gralla, F., Luederitz, C., Lang, D.J., Newig, J., ... Von Wehrden, H. 2013. A review of transdisciplinary research in sustainability science. *Ecological economics*, 92:1-15.

- Braun, V., Clarke, V., Boulton, E., Davey, L. & McEvoy, C. 2021. The online survey as a qualitative research tool. *International Journal of Social Research Methodology*, 24(6):641-654.
<https://doi.org/10.1080/13645579.2020.1805550> 10.1080/13645579.2020.1805550
- Brent, A.C., Oelofse, S. & Godfrey, L. 2008. Advancing the concepts of industrial ecology in South African institutions: science policy. *South African Journal of Science*, 104(1):9-6.
- Brondoni, S.M. 2020. Competitive circular economy management. The Mitsubishi corporation case. *Symphonya. Emerging Issues in Management*:10-25.
- Buckley, P.J. & Michie, J. 1996. *Firms, organizations and contracts: a reader in industrial organization*. Oxford University Press.
- Burke, M.J. & Dunlap, W.P. 2002. Estimating Interrater Agreement with the Average Deviation Index: A User's Guide. *Organizational Research Methods*, 5:159 - 172.
- Burstein, F. & Gregor, S. 1999. The systems development or engineering approach to research in information systems: An action research perspective. In. Proceedings of the 10th Australasian Conference on Information Systems. Victoria University of Wellington, New Zealand. pp. 122-134.
- Butler, M., Epstein, R.A., Totten, A., Whitlock, E.P., Ansari, M.T., Damschroder, L.J., ... Hempel, S. 2017. AHRQ series on complex intervention systematic reviews—paper 3: adapting frameworks to develop protocols. *Journal of clinical epidemiology*, 90:19-27.
- Buzacott, J. 1984. The future of industrial engineering as an academic discipline. *IIE Transactions*, 16(1):35-43.
- Cahyadi, A., Natalisa, D., Poór, J., Perizade, B. & Szabó, K. 2022. Predicting the relationship between green transformational leadership, green human resource management practices, and employees' green behavior. *Administrative Sciences*, 13(1):5.
- Capehart, B.L. 1977. Simulation of continuous system models in industrial engineering. *Computers & Industrial Engineering*, 1(4):207-216.
<https://www.sciencedirect.com/science/article/pii/036083527790002X>
[https://doi.org/10.1016/0360-8352\(77\)90002-X](https://doi.org/10.1016/0360-8352(77)90002-X)
- Catalin, G. & Anca, B. 2015. Strategy From Conceptualization To Competitive Advantage. *Annals of Faculty of Economics*, 1:1109-1119.
- Chang, C.-H. 2011. The influence of corporate environmental ethics on competitive advantage: The mediation role of green innovation. *Journal of business ethics*, 104:361-370.
- Charles, M. & Ochieng, S.B. 2023. Strategic outsourcing and firm performance: a review of literature. *International Journal of Social Science and Humanities Research (IJSSHR)* ISSN:2959-7056.
- Charmaz, K. 2014. *Constructing grounded theory*. sage.
- Chertow, M.R. 2000. Industrial symbiosis: literature and taxonomy. *Annual review of energy and the environment*, 25(1):313-337.
- Chikán, A. 2008. National and firm competitiveness: a general research model. *Competitiveness Review: An International Business Journal*, 18(1/2):20-28.
- Chikán, A., Czakó, E., Kiss-Dobronyi, B. & Losonci, D. 2022. Firm competitiveness: A general model and a manufacturing application. *International Journal of Production Economics*,

243:108316. <https://www.sciencedirect.com/science/article/pii/S0925527321002929>
<https://doi.org/10.1016/j.ijpe.2021.108316>

- Chipunza, C. & Mupani, H. 2019. Environmental influences, employee resourcing strategies and small and medium-sized enterprises performance: Case of South African small restaurants. *SA Journal of Human Resource Management*, 17(1):1-11.
- Chirisa, I. 2008. A population growth and rapid urbanization in Africa: Implications for sustainability.
- Clark, C., Matarrita-Cascante, D., Tkatch, J.R. & Fariha, M.S. 2026. Examining the competitive advantage of nature-based destinations: Applying a holistic resource-based theory framework. *Tourism Management*, 112:105281.
- Collins, H. 2019. *Tacit and explicit knowledge*. University of Chicago press.
- Conradie, P.J. 2010. *Knowledge management as a sustainable competitive advantage in the steel industry*. North-West University.
- Corbin, J. & Strauss, A. 2014. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. SAGE Publications.
- Corcoran, P.B., Walker, K.E. & Wals, A.E. 2004. Case studies, make-your-case studies, and case stories: a critique of case-study methodology in sustainability in higher education. *Environmental Education Research*, 10(1):7-21.
- Corvellec, H., Stowell, A.F. & Johansson, N. 2022. Critiques of the circular economy. *Journal of Industrial Ecology*, 26(2):421-432. <https://doi.org/10.1111/jiec.13187> Date of access: 2024/11/29. <https://doi.org/10.1111/jiec.13187>
- Cowan, D.M., Dopart, P.J., Ferracini, T., Sahmel, J., Merryman, K., Gaffney, S.H. & Paustenbach, D.J. 2010. A cross-sectional analysis of reported corporate environmental sustainability practices. *Regulatory toxicology and pharmacology : RTP*, 58 3:524-538.
- Coyne, K.P. 1986. Sustainable competitive advantage—What it is, what it isn't. *Business horizons*, 29(1):54-61.
- Creswell, J.W. & Creswell, J.D. 2017. *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.
- Cristache, N., Croitoru, G. & Florea, N.V. 2025. The influence of knowledge management on innovation and organizational performance. *Journal of Innovation & Knowledge*, 10(5):100793.
- Cronin, K. 2008. Transdisciplinary research (TDR) and sustainability. *Overview report prepared for the Ministry of Research, Science and Technology*,
- Daily, B.F. & Huang, S.c. 2001. Achieving sustainability through attention to human resource factors in environmental management. *International Journal of operations & production management*, 21(12):1539-1552.
- Dalton, A., Wolff, K. & Bekker, B. 2021. Multidisciplinary Research as a Complex System. *International Journal of Qualitative Methods*, 20:16094069211038400. <https://journals.sagepub.com/doi/abs/10.1177/16094069211038400>
10.1177/16094069211038400
- Dalton, A., Wolff, K. & Bekker, B. 2022. Interdisciplinary Research as a Complicated System. *International Journal of Qualitative Methods*, 21:16094069221100397.

<https://journals.sagepub.com/doi/abs/10.1177/16094069221100397>
10.1177/16094069221100397

- Darian-Smith, E. & McCarty, P. 2016. Beyond interdisciplinarity: Developing a global transdisciplinary framework. *Transcience: A journal of global studies*, 7(2):1-26.
- Darkoh, M.B.K. 2009. An overview of environmental issues in Southern Africa. *African Journal of Ecology*, 47:93-98.
- Darwish, H. 2018. *Expanding industrial thinking by formalizing the industrial engineering identity for the knowledge era*. North-West University.
- Darwish, H. & Van Dyk, L. 2016. The industrial engineering identity: from historic skills to modern values, duties, and roles. *South African Journal of Industrial Engineering*, 27(3):50-63.
- Das, T.K. 2020. *Industrial environmental management: engineering, science, and policy*. John Wiley & Sons.
- Davies, E. & Van der Merwe, K.R. 2016. Methodology to produce a water and energy stream map (WESM) in the South African manufacturing industry. *South African Journal of Industrial Engineering*, 27(3):219-229.
- de Freitas Netto, S.V., Sobral, M.F.F., Ribeiro, A.R.B. & Soares, G.R.d.L. 2020. Concepts and forms of greenwashing: A systematic review. *Environmental Sciences Europe*, 32:1-12.
- De Kock, I.H. 2020. *Managing technology within the context of sustainability transitions: An integrated framework*. Stellenbosch: Stellenbosch University.
- De Kock, I.H. & Brent, A.C. 2022. Exploring the disconnect between the bodies of literature pertaining to socio-technical transitions and technology management (part 2): a linkage analysis. *South African Journal of Industrial Engineering*, 33(1):65-86.
- de Lange, D.E. 2024. Circular economy international trade: An investigation of the relationship between european union circularity and international trade. *Journal of Cleaner Production*, 484:144350. <https://www.sciencedirect.com/science/article/pii/S0959652624037995>
<https://doi.org/10.1016/j.jclepro.2024.144350>
- de Oliveira Neves, F., Salgado, E.G., Ewbank, H. & Sampaio, P. 2024. Construction of taxonomy of conceptualization of sustainability in improving the industrial production process. *International Journal of Quality & Reliability Management*, 41(5):1377-1399.
- De Stefano, M.C., Montes-Sancho, M.J. & Busch, T. 2016. A natural resource-based view of climate change: Innovation challenges in the automobile industry. *Journal of Cleaner Production*, 139:1436-1448.
- De Vos, A.S., Strydom, H., Fouché, C.B. & Delport, C.S.L. 2011. *Research at Grass Roots: For the Social Sciences and Human Service Professions*. Van Schaik Publishers.
- De Vries, M. 2016. Guiding the development of enterprise design approaches. *South African Journal of Industrial Engineering*, 27(3):12-22.
- Dooley, K.J. 2024. The Sustainability Consortium as Action Research. *From Purpose to Impact: The University and Business Partnership*:121.
- Dornyei, Z. 2007. *Research methods in applied linguistics*. Oxford university press.

- Dos Santos, M.A.O. 2009. ACHIEVING SUSTAINABLE COMPETITIVE ADVANTAGE THROUGH THE IMPLEMENTATION OF THE SOCIETAL MARKETING CONCEPT BY A MAJOR RETAILER IN SOUTH AFRICA. *Journal of Global Business and Technology*, 5(2):39-50.
<http://ez.sun.ac.za/login?url=https://www.proquest.com/scholarly-journals/achieving-sustainable-competitive-advantage/docview/216946061/se-2?accountid=14049>
- du Plessis, M.J., van Eeden, J. & Goedhals-Gerber, L.L. 2022. The carbon footprint of fruit storage: a case study of the energy and emission intensity of cold stores. *Sustainability*, 14(13):7530.
- Du Preez, N. & Louw, L. 2007. Managing the knowledge supply chain to support innovation. In. *Proceedings: International Conference on Competitive Manufacturing*. pp. 65-78.
- Du, W.D., Pan, S.L. & Zuo, M. 2013. How to Balance Sustainability and Profitability in Technology Organizations: An Ambidextrous Perspective. *IEEE Transactions on Engineering Management*, 60:366-385.
- Edirisinghe, L., De Alwis, A., Prakash, S. & Wijayasundara, M. 2024. Optimizing material circularity pathways in industrial waste streams: A decision-making model. *MethodsX*, 13:102813.
- Ehrenfeld, J. 2004. Industrial ecology: a new field or only a metaphor? *Journal of cleaner production*, 12(8-10):825-831.
- Eisenhardt, K.M. & Martin, J.A. 2017. Dynamic capabilities: what are they? *The SMS Blackwell handbook of organizational capabilities*:341-363.
- El Shafeey, T. & Trott, P. 2014. Resource-based competition: three schools of thought and thirteen criticisms. *European Business Review*, 26(2):122-148.
- Elheddad, M., Benjasak, C., Deljavan, R., Alharthi, M. & Almagbrok, J.M. 2021. The effect of the Fourth Industrial Revolution on the environment: The relationship between electronic finance and pollution in OECD countries. *Technological Forecasting and Social Change*, 163:120485.
<https://www.sciencedirect.com/science/article/pii/S0040162520313111>
<https://doi.org/10.1016/j.techfore.2020.120485>
- España, S., Condori-Fernandez, N., González, A. & Pastor, Ó. 2010. An empirical comparative evaluation of requirements engineering methods. *Journal of the Brazilian Computer Society*, 16(1):3-19.
- Essuman, A.N., Karikari, F.A., Boateng, S.A., Asongu, S.A. & Fumey, M.P. 2026. An outlook at corporate environmental performance through the lens of green supply chain management, green innovation, sustainable dynamic capabilities, and governance quality in an emerging economy. *Business Strategy and the Environment*, 35(1):1317-1334.
- Farias, L.M.S., Santos, L.C., Gohr, C.F., Oliveira, L.C.d. & Amorim, M.H.d.S. 2019. Criteria and practices for lean and green performance assessment: Systematic review and conceptual framework. *Journal of Cleaner Production*, 218:746-762.
<https://www.sciencedirect.com/science/article/pii/S0959652619304214>
<https://doi.org/10.1016/j.jclepro.2019.02.042>
- Fayemi, P.-E., Maranzana, N., Aoussat, A. & Bersano, G. 2014. Bio-inspired design characterisation and its links with problem solving tools. In. *DS 77: Proceedings of the DESIGN 2014 13th International Design Conference*. pp. 173-182.
- Fengyu, Z., Menghan, L., Xiaowen, X. & He, L. 2026. Green product and process innovation and firm performance: A meta-analytic review. *Sustainability*, 18(3):1640.

- Fercoq, A., Lamouri, S. & Carbone, V. 2016. Lean/Green integration focused on waste reduction techniques. *Journal of Cleaner production*, 137:567-578.
- Fink, A. 2019. *Conducting Research Literature Reviews: From the Internet to Paper*. SAGE Publications.
- Fossey, E., Harvey, C., Mcdermott, F. & Davidson, L. 2002. Understanding and Evaluating Qualitative Research. *Australian & New Zealand Journal of Psychiatry*, 36(6):717-732.
<https://journals.sagepub.com/doi/abs/10.1046/j.1440-1614.2002.01100.x> 10.1046/j.1440-1614.2002.01100.x
- Francis, J.J., Johnston, M., Robertson, C., Glidewell, L., Entwistle, V., Eccles, M.P. & Grimshaw, J.M. 2010. What is an adequate sample size? Operationalising data saturation for theory-based interview studies. *Psychology & Health*, 25(10):1229-1245.
<https://doi.org/10.1080/08870440903194015> 10.1080/08870440903194015
- Fremdling, R. 1997. Industrial revolution and scientific and technological progress. *Jahrbuch für Wirtschaftsgeschichte/Economic History Yearbook*, 38(2):147-168.
- Friedman, K. 2003. Theory construction in design research: criteria: approaches, and methods. *Design studies*, 24(6):507-522.
- Frosch, R.A. & Gallopoulos, N.E. 1989. Strategies for manufacturing. *Scientific American*, 261(3):144-153.
- Fukuda-Parr, S. 2016. From the Millennium Development Goals to the Sustainable Development Goals: shifts in purpose, concept, and politics of global goal setting for development. *Gender & Development*, 24(1):43-52.
- Garcia-Muiña, F.E., González-Sánchez, R., Ferrari, A.M. & Settembre-Blundo, D. 2018. The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company. *Social Sciences*, 7(12):255.
- Garrett, J., Dennis, J.M. & DiSogra, C.A. 2010. Non-response bias: recent findings from address-based panel recruitment. In. Annual Conference of the American Association for Public Opinion Research, Chicago, May. pp. 13-16.
- Garza-Reyes, J.A. 2015. Lean and green – a systematic review of the state of the art literature. *Journal of Cleaner Production*, 102:18-29.
<https://www.sciencedirect.com/science/article/pii/S0959652615004394>
<https://doi.org/10.1016/j.jclepro.2015.04.064>
- Gascoigne, N. & Thornton, T. 2014. *Tacit knowledge*. Routledge.
- Gerolamo, M.C., Carpinetti, L.C.R., Vitoreli, G.A., Sordan, J.E. & Lima, C.H.B. 2014. Quality and safety management systems: Joint action for certification of small firms in an industrial cluster in Brazil. *South african journal of industrial engineering*, 25(1):189-202.
- Gibbs, A. 1997. Focus groups. *Social research update*, 19(8):1-8.
- Gilb, T. 2005. *Competitive engineering: a handbook for systems engineering, requirements engineering, and software engineering using Planguage*. Elsevier.
- Gohar, L. & Shine, K. 2007. Equivalent CO₂ and its use in understanding the climate effects of increased greenhouse gas concentrations. *Weather*, 62(11):307-311.

- Gonyora, A.M., Migiro, S., Ngwenya, B. & Mashau, P. 2021. Investigating open innovation strategic alignment for sustainable competitive advantage in the automotive supply chain in South Africa. *Journal of Transport and Supply Chain Management*, 15:554.
- Gore, A. 2008. *An Inconvenient Truth*. Perfection Learning Corporation.
- Gough, D. & Richardson, M. 2018. Systematic reviews. In. *Advanced research methods for applied psychology*: Routledge. pp. 63-75.
- Gregor, S. & Hevner, A.R. 2013. Positioning and presenting design science research for maximum impact¹. *MIS quarterly*, 37(2):337-355.
- Gregor, S.D., Müller, O. & Seidel, S. 2013. Reflection, Abstraction And Theorizing In Design And Development Research. In. European Conference on Information Systems.
- GRI, U. 2015. Global Compact, & WBCSD.(2015). *SDG Compass: The guide for business action on the SDGs*:4.
- Guest, G., Bunce, A. & Johnson, L. 2006. How many interviews are enough? An experiment with data saturation and variability. *Field methods*, 18(1):59-82.
- Guest, G., MacQueen, K.M. & Namey, E.E.J.A.t.a. 2012. Introduction to applied thematic analysis. 3:20.
- Gummer, T. & Blumenstiel, J.E. 2018. Experimental evidence on reducing nonresponse bias through case prioritization: The allocation of interviewers. *Field Methods*, 30(2):124-139.
- Hadorn, G.H., Hoffmann-Riem, H., Biber-Klemm, S., Grossenbacher-Mansuy, W., Joye, D., Pohl, C., ... Zemp, E. 2008. *Handbook of transdisciplinary research*. 10. Springer.
- Hák, T., Janoušková, S., Moldan, B. & Dahl, A.L. 2018. Closing the sustainability gap: 30 years after “Our Common Future”, society lacks meaningful stories and relevant indicators to make the right decisions and build public support. *Ecological Indicators*, 87:193-195.
<https://www.sciencedirect.com/science/article/pii/S1470160X17307975>
<https://doi.org/10.1016/j.ecolind.2017.12.017>
- Haleem, A., Javaid, M. & Singh, R.P. 2024. Perspective of leadership 4.0 in the era of fourth industrial revolution: A comprehensive view. *Journal of Industrial Safety*, 1(1):100006.
<https://www.sciencedirect.com/science/article/pii/S2950276424000060>
<https://doi.org/10.1016/j.jinse.2024.100006>
- Hanger-Kopp, S., Lemke, L.K.-G. & Beier, J. 2024. What qualitative systems mapping is and what it could be: integrating and visualizing diverse knowledge of complex problems. *Sustainability Science*, 19(3):1065-1078.
- Harreld, J.B., O'Reilly III, C.A. & Tushman, M.L. 2007. Dynamic capabilities at IBM: Driving strategy into action. *California management review*, 49(4):21-43.
- Hart, S.L. 1995. A natural-resource-based view of the firm. *Academy of management review*, 20(4):986-1014.
- Hart, S.L. & Dowell, G. 2011. Invited editorial: A natural-resource-based view of the firm: Fifteen years after. *Journal of management*, 37(5):1464-1479.
- Hart, S.L.J.H.b.r. 1997. Beyond greening: strategies for a sustainable world. 75(1):66-77.

- Hartman, J. 2004. Using focus groups to conduct business communication research. *The Journal of Business Communication* (1973), 41(4):402-410.
- Haskins, B. 2016. Implementing a structured verification framework to improve verification requirements quality. In. INCOSE International Symposium. Wiley Online Library. pp. 877-891.
- Haskins, C. 2007. A systems engineering framework for eco-industrial park formation. *Systems engineering*, 10(1):83-97.
- Hays, P.A. 2003. Case study research. In. *Foundations for research*: Routledge. pp. 233-250.
- Helfat, C.E. & Winter, S.G. 2011. Untangling dynamic and operational capabilities: Strategy for the (N) ever-changing world. *Strategic management journal*, 32(11):1243-1250.
- Helfat, C.E. & Peteraf, M.A. 2015. Managerial cognitive capabilities and the microfoundations of dynamic capabilities. *Strategic management journal*, 36(6):831-850.
- Hemström, K., Simon, D., Palmer, H., Perry, B. & Polk, M. 2021. *Transdisciplinary Knowledge Co-production for Sustainable Cities: A guide for sustainable cities*.
- Hennink, M.M., Kaiser, B.N. & Marconi, V.C. 2017. Code saturation versus meaning saturation: how many interviews are enough? *Qualitative health research*, 27(4):591-608.
- Hesterly, W. & Barney, J. 2014. *Strategic management and competitive advantage*. 28. Pearson/Education Essex.
- Hevner, A., Chatterjee, S., Hevner, A. & Chatterjee, S. 2010. Design science research in information systems. *Design research in information systems: theory and practice*:9-22.
- Hevner, A.R. 2007. A three cycle view of design science research. *Scandinavian journal of information systems*, 19(2):4.
- Hevner, A.R., March, S.T., Park, J. & Ram, S. 2004. Design science in information systems research. *MIS quarterly*, 28(1):75-106.
- Hillman, W. 2022. Interviews in Tourism Research. *Encyclopedia of Tourism Management and Marketing*,
- Hofmann, B., Salomon, H. & Hoffmann, S. 2025. Roles of researchers in inter-and transdisciplinary sustainability research: a reflection tool. *Sustainability science*, 20(3):777-792.
- Hoover, S.P., Rinderle, J.R. & Finger, S. 1991. Models and abstractions in design. *Design Studies*, 12:237-245.
- Hoque, A., Mohiuddin, M. & Su, Z. 2018. Effects of industrial operations on socio-environmental and public health degradation: evidence from a least developing country (LDC). *Sustainability*, 10(11):3948.
- House, E.R. 1991. Realism in research. *Educational researcher*, 20(6):2-9.
- Huang, C.-J., Liu, H.-Y., Lin, T.-L. & Lai, J.-Y. 2024. Revisiting Hofstede's dimensions of national culture and environmental sustainability. *Energy & Environment*, 35(3):1251-1269.
- IISE, I.o.I.a.S.E. 2023. *What is industrial and systems engineering? (IISE official definition)*.
- INCOSE. 2023. *INCOSE systems engineering handbook*. John Wiley & Sons.

- Insights, I. 2026. *Sustainability as a Competitive Advantage*.
<https://insights.issgovernance.com/posts/sustainability-as-a-competitive-advantage/> Date of access:
- Jacob, J. 2025. A background history of the sustainable development goals. *Sustainable Development*, 33(3):3747-3759.
- Jacobs, F.R. & Chase, R.B. 2018. *Operations and supply chain management*. McGraw-Hill.
- Jacobson, I., Christerson, M., Jonsson, P. & Overgaard, G. 1992. *Object-Oriented Systems Engineering: A Use-case Driven Approach*. Addison-Wesley.
- Jawahir, I.S. & Bradley, R. 2016. Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing. *Procedia Cirp*, 40:103-108.
- Jin, G., Fu, R., Li, Z., Wu, F. & Zhang, F. 2018. CO2 emissions and poverty alleviation in China: An empirical study based on municipal panel data. *Journal of Cleaner Production*, 202:883-891.
<https://www.sciencedirect.com/science/article/pii/S0959652618325708>
<https://doi.org/10.1016/j.jclepro.2018.08.221>
- Johnson, S.L. 2010. Research and statistics: a question of time: cross-sectional versus longitudinal study designs. *Pediatrics in review*, 31 6:250-251.
- Jovanovic, V. 2013. Multidisciplinary design and modern manufacturing as driving forces for industrial engineers of a future. *Chap*, 60:969-984.
- Karuppusamy, M., Palanisamy, S., Gurusamy, M., Balasubramanian, V.P., Jayamani, M., Sankar, S.L., ... Palaniappan, M. 2026. Biomimetic and Bioinspired Materials: Design Strategies, Mechanical Properties, and Engineering Applications—A Review. *Global Challenges*, 10(3):e70101.
- Kasa, S. 1973. Industrial revolutions and environmental problems. *Confluence*, 1941:70.
- Kasirye, F. 2024. An overview of mixed and multi method research. *Authorea Preprints*,
- Kawulich, B.B. 2005. Participant observation as a data collection method. In. Forum: Qualitative Social Research/Qualitative Sozialforschung. p 1.
- Kennedy, E., Fecheyr-Lippens, D., Hsiung, B.-K., Niewiarowski, P.H. & Kolodziej, M. 2015. Biomimicry: A path to sustainable innovation. *Design Issues*, 31(3):66-73.
- Kennedy, E.B. & Marting, T.A. 2016. Biomimicry: Streamlining the Front End of Innovation for Environmentally Sustainable Products: Biomimicry can be a powerful design tool to support sustainability-driven product development in the front end of innovation. *Research-Technology Management*, 59(4):40-48.
- Khaleghi, M., Sheykhivand, S., Khaleghi, N. & Danishvar, S. 2026. An Intelligent Multi-Task Supply Chain Model Based on Bio-Inspired Networks. *Biomimetics*, 11(2):123.
- Khallaf, M. 2011. *The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources*. IntechOpen.
- Khanmirzaee, S., Jafari, M., Makui, A. & Teimoury, E. 2025. Research perspectives of supply chain knowledge management: A bibliometrics study. *Journal of Information Science*, 51(2):523-536.

- Klausbruckner, C., Henneman, L.R., Rafaj, P. & Annegarn, H.J. 2018. Energy policy, air quality, and climate mitigation in South Africa: The case for integrated assessment. In. *Systems analysis approach for complex global challenges*: Springer. pp. 113-138.
- Knierim, A. & Callenius, C. 2018. Transdisciplinary approaches and methods in the context of food and nutrition security. *World Rev. Nutr. Diet*, 118:144-151.
- Koskela, L. & Kagioglou, M. 2005. On the metaphysics of production. 13th Inter-national Group for Lean Construction Conference. *Sydney, Australia*,
- Kostoska, O. & Kocarev, L. 2019. A novel ICT framework for sustainable development goals. *Sustainability*, 11(7):1961.
- Kraaijenbrink, J., Spender, J.-C. & Groen, A.J. 2010. The resource-based view: A review and assessment of its critiques. *Journal of management*, 36(1):349-372.
- Kroeze, I.J. 2013. Legal research methodology and the dream of interdisciplinarity. *Potchefstroom Electronic Law Journal/Potchefstroomse Elektroniese Regsblad*, 16(3):35-65.
- Kvale, S. 1996. *InterViews: an introduction to qualitative research interviewing*. Sage.
- Lang, D.J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., ... Thomas, C.J. 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science*, 7:25-43.
- Le Grand, J. & Roberts, J. 2021. Hands, hearts and hybrids: economic organization, individual motivation and public benefit. *LSE Public Policy Review*, 1(3),
- Lewis, H. 2017. *Product stewardship in action: the business case for life-cycle thinking*. Routledge.
- Li, J., Jeffery, R., Fung, K.H., Zhu, L., Wang, Q., Zhang, H. & Xu, X. 2012. A business process-driven approach for requirements dependency analysis. In. *International Conference on Business Process Management*. Springer. pp. 200-215.
- Li, X., Liu, D., Sun, J. & Zhu, Z. 2022. Challenges of Industrial Engineering in Big Data Environment and Its new Directions on Extension Intelligence. *Procedia Computer Science*, 214:1561-1567. <https://www.sciencedirect.com/science/article/pii/S1877050922020567>
<https://doi.org/10.1016/j.procs.2022.11.344>
- Lin, W.L., Chong, S.C. & Wong, K.K.S. 2025. Sustainable development goals and corporate financial performance: Examining the influence of stakeholder engagement. *Sustainable Development*, 33(2):2714-2739.
- Llieva, L., Ursano, I., Traista, L., Hoffmann, B. & Dahy, H. 2022. Biomimicry as a Sustainable Design Methodology—Introducing the ‘Biomimicry for Sustainability’ Framework. *Biomimetics*, 7,
- Lubis, N.W. 2022. Resource based view (RBV) in improving company strategic capacity. *Research Horizon*, 2(6):587-596.
- Lüdeke-Freund, F., Gold, S. & Bocken, N. 2017. Sustainable business model and supply chain conceptions: Towards an integrated perspective. In. *Implementing triple bottom line sustainability into global supply chains*: Routledge. pp. 345-372.
- Machingura, T., Adetunji, O. & Maware, C. 2024a. The mediatory role of the environmental performance function within the lean-green manufacturing sustainability complex. *The TQM Journal*,

- Machingura, T., Adetunji, O. & Maware, C. 2024b. A hierarchical complementary Lean-Green model and its impact on operational performance of manufacturing organisations. *International Journal of Quality & Reliability Management*, 41(2):425-446.
- Maggio, L.A., Tannery, N.H. & Kanter, S.L. 2011. Reproducibility of literature search reporting in medical education reviews. *Academic Medicine*, 86(8):1049-1054.
- Malterud, K. 2012. Systematic text condensation: a strategy for qualitative analysis. *Scand J Public Health*, 40(8):795-805. 10.1177/1403494812465030
- Mangaroo-Pillay, M. 2022. *A Lean implementation framework encompassing South African Ubuntu*. North-West University (South Africa).
- Mangaroo-Pillay, M. & Roopa, M. 2021. Beyond the industrial engineering frontier: A few steps in history and a giant leap into the future. *South African Journal of Industrial Engineering*, 32(3):1-9.
- Mangaroo-Pillay, M., Coetzee, R.J.J.o.I.E. & Management. 2022. Lean frameworks: A systematic literature review (SLR) investigating methods and design elements. 15(2):202-214.
- Mangaroo-Pillay, M., Roopa, M. & Maisiri, W. 2023. Could digital Ubuntu be the South African version of industry 4.0? *South African Journal of Industrial Engineering*, 34(1):1-12.
- Maráková, V., Wolak-Tuzimek, A., Lament, M. & Dzúriková, L. 2023. The competitive advantage of enterprises from the customer perspective.
- Markley, M.J. & Davis, L. 2007. Exploring future competitive advantage through sustainable supply chains. *International Journal of Physical Distribution & Logistics Management*, 37(9):763-774.
- Markovitz, A.R., Goldstick, J.E., Levy, K., Cevallos, W., Mukherjee, B., Trostle, J.A. & Eisenberg, J.N.S. 2012. Where science meets policy: comparing longitudinal and cross-sectional designs to address diarrhoeal disease burden in the developing world. *International journal of epidemiology*, 41 2:504-513.
- Martin, P.Y. & Turner, B.A. 1986. Grounded Theory and Organizational Research. *The Journal of Applied Behavioral Science*, 22(2):141-157.
<https://journals.sagepub.com/doi/abs/10.1177/002188638602200207>
 10.1177/002188638602200207
- Massaro, M., Dumay, J. & Guthrie, J. 2016. On the shoulders of giants: undertaking a structured literature review in accounting. *Accounting, Auditing & Accountability Journal*, 29(5):767-801.
- Mazza, R. & Berre, A. 2007. Focus group methodology for evaluating information visualization techniques and tools. In. 2007 11th International Conference Information Visualization (IV'07). IEEE. pp. 74-80.
- McGrath, R.G. 2013. *The end of competitive advantage: How to keep your strategy moving as fast as your business*. Harvard Business Review Press.
- McNiff, J. 2013. *Action research: Principles and practice*. Routledge.
- Meidute-Kavaliauskiene, I., Çiğdem, Ş., Vasilis Vasiliauskas, A. & Yıldız, B. 2021. Green innovation in environmental complexity: The implication of open innovation. *Journal of Open Innovation: Technology, Market, and Complexity*, 7(2):107.

- Mert, E., Aksu, M. & Celiktaş, M.S. 2025. Projections of global energy transition models in the wake of industrial revolution and climate change policies. *Clean Energy Science and Technology*, 3(1):273.
- Michelfelder, D. & Jones, S.A. 2013. Sustaining engineering codes of ethics for the twenty-first century. *Science and Engineering Ethics*, 19(1):237-258.
- Milberg Muñiz, E., Ludwig, D. & El-Hani, C.N. 2025. Research as a Mangrove: Emancipatory science and the messy reality of transdisciplinarity. *International Review of Qualitative Research*, 18(2):237-259.
- Mishra, N., White, R.W., leong, S. & Horvitz, E. 2014. Time-critical search. In. Proceedings of the 37th international ACM SIGIR conference on Research & development in information retrieval. pp. 747-756.
- Mohsin, A., Schmidt, V., Aschauer, F., Plasch, M. & Gerschberger, M. 2025. Examining the evolution of sustainable supply chain management: A systematic review and bibliometric analysis. *Sustainable Development*, 33(6):8213-8238.
- Monat, J.P. & Gannon, T.F. 2015. What is Systems Thinking? A Review of Selected Literature Plus Recommendations. In.
- Monica Chiarini, T., Hevner, A.R. & Berndt, D.J. 2010. Focus Groups for Artifact Refinement and Evaluation in Design Research. *Communications of the Association for Information Systems*, 26:27. <http://ez.sun.ac.za/login?url=https://www.proquest.com/scholarly-journals/focus-groups-artifact-refinement-evaluation/docview/2500534429/se-2?accountid=14049>
<https://doi.org/10.17705/1CAIS.02627>
- Montgomery, D.C. 2017. *Design and Analysis of Experiments*. John Wiley & Sons, Incorporated.
- Mora-Contreras, R. & Carrillo-Hermosilla, J. 2025. Revealing the effects of circular economy, eco-innovation and industry 4.0 on sustainability performance and competitive advantage in manufacturing companies. *Sustainable Development*, 33:1249-1270.
- Morelli, J. 2011. Environmental sustainability: A definition for environmental professionals. *Journal of environmental sustainability*, 1(1):2.
- Morgan, D. 1993. Focus groups and surveys. In. Annual Meeting of the American Sociological Association. Pittsburgh, PA.
- Morgan, D.L. 1996. *Focus groups as qualitative research*. 16. Sage publications.
- Moustabchir, A., Ouakil, H. & Ouazzani, H.E.L. 2024. Modeling the circular economy in food production: insights from a dynamic stochastic general equilibrium analysis. *Scientific African*, 26:e02479. <https://www.sciencedirect.com/science/article/pii/S2468227624004216>
<https://doi.org/10.1016/j.sciaf.2024.e02479>
- Moynihan, G. 2021. *Concepts, applications and emerging opportunities in industrial engineering*. BoD—Books on Demand.
- Musante, K. & DeWalt, B.R. 2010. *Participant observation: A guide for fieldworkers*. Bloomsbury Publishing PLC.
- N'dri, L.M., Islam, M. & Kakinaka, M. 2021. ICT and environmental sustainability: Any differences in developing countries? *Journal of Cleaner Production*, 297:126642. <https://www.sciencedirect.com/science/article/pii/S0959652621008623>
<https://doi.org/10.1016/j.jclepro.2021.126642>

- Nath, S., Pillai, A.A., Ram, A., Gayathri, A.N., Viswanath, N., Tanjeri, P., ... Arulprasad, R. 2025. Quantitative analysis to identify circular economy concepts incorporated in Indian policy documents regulating waste management by the Indian Healthcare sector. *Resources, Conservation and Recycling*, 214:108037.
<https://www.sciencedirect.com/science/article/pii/S092134492400627X>
<https://doi.org/10.1016/j.resconrec.2024.108037>
- Nations, U. 2015. Transforming our world: The 2030 agenda for sustainable development. *New York: United Nations, Department of Economic and Social Affairs*, 1:41.
- Ndoka, E., Alimehmeti, G., Shulla, K. & Voigt, B.-F. 2025. Transitioning to circular business models in developing countries: a systematic literature review of barriers, enablers, and future directions. *Discover Sustainability*, 6(1):605.
- Ndoricimpa, A. 2017. Analysis of asymmetries in the nexus among energy use, pollution emissions and real output in South Africa. *Energy*, 125:543-551.
<http://www.sciencedirect.com/science/article/pii/S0360544217302396>
<https://doi.org/10.1016/j.energy.2017.02.065>
- Noesgaard, S.S. & Ørngreen, R. 2015. The effectiveness of e-learning: An explorative and integrative review of the definitions, methodologies and factors that promote e-Learning effectiveness. *Electronic Journal of e-Learning*, 13:278-290.
- Nonaka, I. 2009. The knowledge-creating company. In. *The economic impact of knowledge*: Routledge. pp. 175-187.
- Nonaka, I. & Takeuchi, H. 1995. *The knowledge-creating company: How Japanese companies create the dynamics of innovation*. Oxford university press.
- Nonaka, I. & Nishiguchi, T. 2001. *Knowledge emergence: Social, technical, and evolutionary dimensions of knowledge creation*. Oxford University Press.
- Nonaka, I. & Takeuchi, H. 2007. The knowledge-creating company. *Harvard business review*, 85(7/8):162.
- Nunamaker Jr, J.F., Chen, M. & Purdin, T.D. 1990. Systems development in information systems research. *Journal of management information systems*, 7(3):89-106.
- O'Raghallaigh, P., Sammon, D. & Murphy, C. 2012. Using focus groups to evaluate artefacts in design research. In. *The 6th European Conference on Information Management and Evaluation* University College Cork. pp. 251-257.
- Onwe, J.C., Ullah, E., Ansari, M.A., Sahoo, M. & Dhayal, K.S. 2024. Industrialization meets sustainability: Analysing the role of technological innovations, energy efficiency and urbanisation for major industrialized economies. *Journal of Environmental Management*, 372:123297.
- Opdenakker, R.R. 2006. Advantages and disadvantages of four interview techniques in qualitative research. *Forum Qualitative Social Research*, 7:10.
- Ozsoy, C.M. & Mengüç, M.P. 2024. A transdisciplinary approach and design thinking methodology: For applications to complex problems and energy transition. *World*, 5(1):119-135.
- Palmer, J., Smith, T., Willetts, J. & Mitchell, C. 2009. Creativity, ethics and transformation: Key factors in a transdisciplinary application of systems methodology to resolving wicked problems in sustainability. *Systemic development: Local solutions in a global environment*,

- Park, Y.S., Konge, L. & Artino Jr, A.R. 2020. The positivism paradigm of research. *Academic medicine*, 95(5):690-694.
- Parkhe, A. 2026. Epistemology of bridging the theory-practice gap in strategic management. *Strategic Management Review*, 7(2):118-144.
- Parnell, G.S., Kenley, C.R., Specking, E. & Pohl, E. 2022. Systems Engineering and Industrial Engineering. *INCOSE International Symposium*, 32,
- Paterson, B., Isaacs, M., Hara, M., Jarre, A. & Moloney, C. 2010. Transdisciplinary co-operation for an ecosystem approach to fisheries: a case study from the South African sardine fishery. *Marine Policy*, 34(4):782-794.
- Pearce, D.W. & Turner, R.K. 1989. *Economics of natural resources and the environment*. Johns Hopkins University Press.
- Peffer, K., Tuunanen, T., Rothenberger, M.A. & Chatterjee, S. 2007. A design science research methodology for information systems research. *Journal of management information systems*, 24(3):45-77.
- Peruzzini, M., Wognum, N., Bil, C. & Stjepandić, J. 2020. Special issue on 'transdisciplinary approaches to digital manufacturing for industry 4.0'. *International Journal of Computer Integrated Manufacturing*, 33:321 - 324.
- Peteraf, M.A. & Barney, J.B. 2003. Unraveling the resource-based tangle. *Managerial and decision economics*, 24(4):309-323.
- Piirainen, K.A. & Briggs, R.O. 2011. Design theory in practice—making design science research more transparent. In. Service-Oriented Perspectives in Design Science Research: 6th International Conference, DESRIST 2011, Milwaukee, WI, USA, May 5-6, 2011. Proceedings 6. Springer. pp. 47-61.
- Piñeiro-Chousa, J., Vizcaíno-González, M., López-Cabarcos, M.Á. & Romero-Castro, N. 2017. Managing Reputational Risk through Environmental Management and Reporting: An Options Theory Approach. *Sustainability*, 9:1-15.
- Pirela, C.V., Plata, A.O. & Hernandez, G.L. 2024. Strategic thinking as a potential factor in the growth of companies in the dairy sector. *Management (Montevideo)*, 2:40-40.
- Poliandri, D., Perazzolo, M., Pillera, G.C. & Giampietro, L. 2023. Dematerialized participation challenges: Methods and practices for online focus groups. *Frontiers in Sociology*, 8:1145264.
- Polk, M. 2015. Transdisciplinary co-production: Designing and testing a transdisciplinary research framework for societal problem solving. *Futures*, 65:110-122.
<https://www.sciencedirect.com/science/article/pii/S0016328714001864>
<https://doi.org/10.1016/j.futures.2014.11.001>
- Popescu, G., Boboc, D., Stoian, M., Zaharia, A. & Lădaru, G.R. 2017. A Cross-Sectional Study of Sustainability Assessment. *Economic Computation and Economic Cybernetics Studies and Research*, 51:21-36.
- Poth, C.N. 2018. Innovation in mixed methods research: A practical guide to integrative thinking with complexity.
- Priem, R.L. & Butler, J.E. 2001. Is the resource-based “view” a useful perspective for strategic management research? *Academy of management review*, 26(1):22-40.

- Pronk, N.P. & Lee, B.Y. 2024. Qualitative systems mapping in promoting physical activity and cardiorespiratory fitness: perspectives and recommendations. *Progress in Cardiovascular Diseases*, 83:43-48.
- Qi, Y., Bhunia, P., Zhang, T.C., Luo, F., Lin, P. & Chen, Y. 2020. Environmental degradation and sustainability. *Sustainability: fundamentals and applications*:483-505.
- Rahem, M.A. & Darrah, M. 2018. Using a computational approach for generalizing a consensus measure to Likert scales of any size n. *International Journal of Mathematics and Mathematical Sciences*, 2018,
- Rahubadda, R.V.A.D., Manewa, A., Anagal, V. & Siriwardena, M. 2025. The Wood Wide Web as a blueprint for carbon-neutral cities: a biomimetic model for adaptive energy sharing. *Frontiers in Built Environment*, 11:1681714.
- Ranis, G. 2004. Human development and economic growth.
- Rindfleisch, A., Malter, A.J., Ganesan, S. & Moorman, C. 2008. Cross-Sectional versus Longitudinal Survey Research: Concepts, Findings, and Guidelines. *Journal of Marketing Research*, 45:261 - 279.
- Rizzi, F., Gusmerotti, N. & Frey, M. 2020. How to meet reuse and preparation for reuse targets? Shape advertising strategies but be aware of "social washing". *Waste Management*, 101:291-300. <https://www.sciencedirect.com/science/article/pii/S0956053X19306555>
<https://doi.org/10.1016/j.wasman.2019.10.024>
- Robé, J.-P. 2022. Firms versus corporations: a rebuttal of simon deakin, david gindis, and geoffrey m. hodgson. *Journal of Institutional Economics*, 18(4):693-701.
- Robinson, G. 2021. Capturing a moving target: Interviewing fintech experts via LinkedIn. *Area*, 53(4):671-678.
- Rodriguez, M.A., Ricart, J.E. & Sanchez, P. 2002. Sustainable development and the sustainability of competitive advantage: A dynamic and sustainable view of the firm. *Creativity and innovation management*, 11(3):135-146.
- Roman, A.V.J.J.o.c.p. 2017. Institutionalizing sustainability: A structural equation model of sustainable procurement in US public agencies. 143:1048-1059.
- Roopa, M. 2021. *Designing a Lean and Green framework for the reduction of GHG emissions in the South African manufacturing industry*. North-West University (South Africa).
- Roopa, M. 2023. Business Engineering 4.0: The Transformation of a University Course in Response to Industry 4.0, Sustainable Development Goals, & Covid-19 in South Africa. *International Journal of Engineering Pedagogy*, 13(8),
- Roopa, M. 2024. *An Industrial Engineering Lighthouse Model for Transdisciplinary Problem Solving and Sustainable Development in South Africa*. Paper presented at the SAIE 34 - Illuminate, Riverside Sun, Vanderbijlpark, South Africa.
- Roopa, M., Coetzee, R. & Davies, E. 2020. Designing a Lean and Green framework for GHG reduction in the South African manufacturing industry.
- Roopa, M., Siriram, R. & Coetzee, R. 2024. Exploring Industrial Engineering Knowledge and Environmental Sustainability. *Sustainability*, 16(17):7392. <https://www.mdpi.com/2071-1050/16/17/7392>

- Royer, S. & Simon, M. 2024. Strategic Capabilities in Sustainability-oriented Value Chains in the Northern German Agri-Food Ecosystem—a Natural-Resource-based View Perspective. *mrev management review*, 35(1):10-34.
- RSA, S.A.G. 2000. Engineering Profession Act. 2000. 426,
- Sabharwal, S., Kaur, P. & Sibal, R. 2017. Empirical and Theoretical Validation of a Use Case Diagram Complexity Metric. *International Journal of Information Technology and Computer Science*, 9(11):35-47.
- Sachdeva, A., Sharma, V.S. & Singh, J. 2019. Recent advances in industrial engineering. *Journal of Manufacturing Technology Management*, 30(6):897-898.
- Sadler, G.R., Lee, H.C., Lim, R.S.H. & Fullerton, J. 2010. Recruitment of hard-to-reach population subgroups via adaptations of the snowball sampling strategy. *Nursing & health sciences*, 12(3):369-374.
- Sakao, T. & Brambila-Macias, S.A. 2018. Do we share an understanding of transdisciplinarity in environmental sustainability research? *Journal of Cleaner Production*, 170:1399-1403.
- Salvendy, G. 2001. *Handbook of industrial engineering: technology and operations management*. John Wiley & Sons.
- Saunders, M., Lewis, P. & Thornhill, A. 2009. *Research methods for business students*. Pearson education.
- Sauvé, S., Bernard, S. & Sloan, P. 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development*, 17:48-56. <https://www.sciencedirect.com/science/article/pii/S2211464515300099>
<https://doi.org/10.1016/j.envdev.2015.09.002>
- Schindel, W.D. 2024. What is the Smallest Model of a System? *Insight*, 27(4):43-52.
- Schlüter, L., Kørnøv, L., Mortensen, L., Løkke, S., Storrs, K., Lyhne, I. & Nors, B. 2023. Sustainable business model innovation: Design guidelines for integrating systems thinking principles in tools for early-stage sustainability assessment. *Journal of Cleaner Production*, 387:135776. <https://www.sciencedirect.com/science/article/pii/S0959652622053501>
<https://doi.org/10.1016/j.jclepro.2022.135776>
- Schmidt, F.L. & Hunter, J.E. 1978. MODERATOR RESEARCH AND THE LAW OF SMALL NUMBERS 1. *Personnel Psychology*, 31(2):215-232.
- Schmidt, M. 2008. The Sankey diagram in energy and material flow management: Part I: History. *Journal of industrial ecology*, 12(1):82-94.
- Schneider, G. & Winters, J.P. 2001. *Applying Use Cases: A Practical Guide*. Pearson Education.
- Schneider, J.M. 2000. Focus Groups for Libraries and Librarians. *Bulletin of the Medical Library Association*, 88(3):280.
- Schutte, C.S., Kennon, D. & Bam, W. 2016. The status and challenges of industrial engineering in South Africa. *South African Journal of Industrial Engineering*, 27(1):1-19.
- Schwarz, R.M. 1994. *The Skilled Facilitator: Practical Wisdom for Developing Effective Groups*. A Joint Publication in the Jossey-Bass Management, Public Administration, and Nonprofit Sector Series. ERIC.

- Seufert, A., Von Krogh, G. & Back, A. 2004. *Towards knowledge networking*. Springer.
- Severo, E.A., De Guimarães, J.C.F. & Dellarmelin, M.L. 2021. Impact of the COVID-19 pandemic on environmental awareness, sustainable consumption and social responsibility: Evidence from generations in Brazil and Portugal. *Journal of cleaner production*, 286:124947.
- Shahzad, I. & Soroya, S.H. 2025. Integrating tacit knowledge transfer model in academic context: A SEM analysis approach. *Journal of the Knowledge Economy*, 16(4):14500-14527.
- Sharma, G., Prasad, C. & Srinivasa Rao, M. 2021. Industrial engineering into healthcare—A comprehensive review. *International Journal of Healthcare Management*, 14(4):1288-1302.
- Sharma, R. & Gupta, H. 2024. Harmonizing sustainability in industry 5.0 era: Transformative strategies for cleaner production and sustainable competitive advantage. *Journal of Cleaner Production*, 445:141118.
- Shrivastava, P., Ivanaj, S. & Persson, S. 2013. Transdisciplinary study of sustainable enterprise. *Business Strategy and the Environment*, 22(4):230-244.
- Shuen, A., Feiler, P.F. & Teece, D.J. 2014. Dynamic capabilities in the upstream oil and gas sector: Managing next generation competition. *Energy Strategy Reviews*, 3:5-13.
- Simon, J.S. 1999. The Wilder Nonprofit Field Guide to Conducting Successful Focus Groups. In.
- Siriram, R. 2023. Integrating and transitioning the project front-end and project initiation phases in South African electrical engineering industrial projects. *International Journal of Managing Projects in Business*, 16(8):1-26.
- Slife, B.D. & Williams, R.N. 1995. *What's behind the research?: Discovering hidden assumptions in the behavioral sciences*. Sage.
- Smith, E.A. 2001. The role of tacit and explicit knowledge in the workplace. *Journal of knowledge Management*, 5(4):311-321.
- Soini, K. & Dessein, J. 2016. Culture-sustainability relation: Towards a conceptual framework. *Sustainability*, 8(2):167.
- Sołoducho-Pelc, L. & Sulich, A. 2020. Between sustainable and temporary competitive advantages in the unstable business environment. *Sustainability*, 12(21):8832.
- Somé, S.S. 2005. Use cases based requirements validation with scenarios. In. 13th IEEE International Conference on Requirements Engineering (RE'05). IEEE. pp. 465-466.
- Somerville, M. & Rapport, D.J. 2002. *Transdisciplinarity: reCreating Integrated Knowledge*. McGill-Queen's University Press.
- Sovacool, B.K., Iskandarova, M. & Hall, J. 2023. Industrializing theories: A thematic analysis of conceptual frameworks and typologies for industrial sociotechnical change in a low-carbon future. *Energy Research & Social Science*, 97:102954.
- Sperotto, F. 1994. *In the Footsteps of Homo Industrialis: A Chronology of Industry and Industrial Engineering*. Picsie Press.
- Spillers, W. & Newsome, S. 1988. Some attributes of design theory. *Civil Engineering Systems*, 5(4):194-198.

- Srivastava, M., Franklin, A. & Martinette, L. 2013. Building a sustainable competitive advantage. *Journal of technology management & innovation*, 8(2):47-60.
- Stock, P. & Burton, R.J. 2011. Defining terms for integrated (multi-inter-trans-disciplinary) sustainability research. *Sustainability*, 3(8):1090-1113.
- Strauss, A. & Corbin, J. 1990. *Basics of qualitative research*. 15. sage Newbury Park, CA.
- Susman, G.I. & Evered, R.D. 2023. An assessment of the scientific merits of action research. *Studi organizzativi*, (2022/2),
- Swain, R.B. 2018. A critical analysis of the sustainable development goals. *Handbook of sustainability science and research*:341-355.
- Tang, K.C. & Davis, A. 1995. Critical factors in the determination of focus group size. *Family practice*, 12 4:474-475.
- Tanwar, R. 2013. Porter's generic competitive strategies. *IOSR Journal of Business and Management*, 15(1):11-17.
- Tarozzi, M. 2020. *What is grounded theory?* Bloomsbury publishing.
- Teece, D.J. 2007. Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. *Strategic management journal*, 28(13):1319-1350.
- Teece, D.J., Pisano, G. & Shuen, A. 1997. Dynamic capabilities and strategic management. *Strategic management journal*, 18(7):509-533.
- Templ, B., Templ, M., van Chinh, A.N.G. & Brändle, U. 2025. Leveraging Sankey diagrams for enhanced curriculum planning in higher education. *Curriculum Journal*, 36(1):202.
- Thekkoote, R. 2022. A framework for the integration of lean, green and sustainability practices for operation performance in South African SMEs. *International Journal of Sustainable Engineering*, 15(1):47-58.
- Thomas, D.R. 2003. A general inductive approach for qualitative data analysis.
- Thompson, R., Bandera, E., Burley, V., Cade, J., Forman, D., Freudenheim, J., ... Kushi, L. 2008. Reproducibility of systematic literature reviews on food, nutrition, physical activity and endometrial cancer. *Public health nutrition*, 11(10):1006-1014.
- Ting, H., Memon, M.A., Thurasamy, R. & Cheah, J.-H. 2025. Snowball sampling: A review and guidelines for survey research. *Asian Journal of Business Research*, 15(1),
- Tiwari, P., Sadeghi, J.K. & Eseonu, C. 2020. A sustainable lean production framework with a case implementation: Practice-based view theory. *Journal of Cleaner Production*, 277:123078.
- Toktas-Palut, P., Onan, K., Gürbüz, M.Z. & Gülden-Özdemir, B. 2022. Moss Software: A New Tool for Multi-Objective Green Supplier Selection. *International Journal of Industrial Engineering: Theory, Applications and Practice*, 29(2),
- Tress, G., Tress, B. & Fry, G. 2005. Clarifying integrative research concepts in landscape ecology. *Landscape ecology*, 20:479-493.
- Turok, I. & Borel-Saladin, J. 2014. Is urbanisation in South Africa on a sustainable trajectory? *Development Southern Africa*, 31(5):675-691.

- van Aken, J.E. & Berends, H. 2018. *Problem Solving in Organizations*. Cambridge University Press.
- Van den Bergh, J. 2004. Firm behaviour and organisation from an evolutionary perspective. *Entrepreneurship and Regional Economic Development. A Spatial Perspective, Cheltenham, UK, and Northampton, MA, USA: Edward Elgar*:15-45.
- van der Linde, N. & Roopa, M. 2021. Designing a decision support system for workforce planning in a South African tertiary institution.
- Van Manen, M. 2001. Transdisciplinarity and the new production of knowledge. *Qualitative Health Research*, 11(6):850-852.
- Varsei, M. 2019. Sustainable supply chain design. *Handbook on the Sustainable Supply Chain*:242-260.
- Vasileiou, K., Barnett, J., Thorpe, S. & Young, T. 2018. Characterising and justifying sample size sufficiency in interview-based studies: systematic analysis of qualitative health research over a 15-year period. *BMC medical research methodology*, 18:1-18.
- Vedder, D., Fischer, S.M., Wiegand, K. & Pe'er, G. 2024. Developing multidisciplinary mechanistic models: challenges and approaches. *Socio-Environmental Systems Modelling*, 6:18701-18701.
- Verrier, B., Rose, B. & Caillaud, E.J.J.o.c.p. 2016. Lean and Green strategy: the Lean and Green House and maturity deployment model. 116:150-156.
- Veselica Celić, R. 2025. INNOVATION STRATEGIES AND ORGANIZATIONAL COMPETITIVENESS. In. DIEM: Dubrovnik International Economic Meeting. Sveučilište u Dubrovniku. pp. 109-118.
- Vezzoli, C. & Manzini, E. 2008. *Design for environmental sustainability*. Springer.
- Villar, R., Olmo, M., Atienza, P., Garzón, A.J., Wright, I.J., Poorter, H. & Hierro, L.A. 2021. Applying the economic concept of profitability to leaves. *Scientific Reports*, 11(1):49. <https://doi.org/10.1038/s41598-020-79709-w> 10.1038/s41598-020-79709-w
- Wada, M., Grigorovich, A., Kontos, P., Fang, M.L. & Sixsmith, J. 2020. Addressing real-world problems through transdisciplinary working. In. *Knowledge, Innovation, and Impact: A Guide for the Engaged Health Researcher: A Guide for the Engaged Health Researcher*. Springer. pp. 121-129.
- Wang, N., Bai, Y., Guo, Z., Fan, Y. & Meng, F. 2024. Synergies between the circular economy and carbon emission reduction. *Science of The Total Environment*, 951:175603. <https://www.sciencedirect.com/science/article/pii/S0048969724057590> <https://doi.org/10.1016/j.scitotenv.2024.175603>
- Wang, W.-C., Lin, C.-H. & Chu, Y.-C. 2011. Types of competitive advantage and analysis. *International Journal of Business and Management*, 6(5):100.
- Wang, X., Xiao, L., Fan, L., Mokhtar, N.A. & Mat Sulaiman, M.K.A. 2025. Application of bionic architecture in low-carbon design: a systematic review from nature inspiration to architectural practice. *Frontiers in Built Environment*, 11:1652481.
- Waqas, M., Honggang, X., Ahmad, N., Khan, S.A.R. & Iqbal, M. 2021. Big data analytics as a roadmap towards green innovation, competitive advantage and environmental performance. *Journal of Cleaner Production*, 323:128998.

<https://www.sciencedirect.com/science/article/pii/S0959652621031887>
<https://doi.org/10.1016/j.jclepro.2021.128998>

- Weaich, M., Simbanegavi, P., Ndlovu, P., Root, D., Bedi, T., Parafiniuk, A., ... Schmitz, G. 2024. Achieving Sustainable Transdisciplinary Research in Construction Project Management. Available at SSRN 4910356,
- Welch, C. 2000. The archaeology of business networks: the use of archival records in case study research. *Journal of Strategic Marketing*, 8(2):197-208.
- Wernerfelt, B. 1984. A resource-based view of the firm. *Strategic management journal*, 5(2):171-180.
- Wieczorek, A.J. 2018. Sustainability transitions in developing countries: Major insights and their implications for research and policy. *Environmental Science & Policy*, 84:204-216.
<https://www.sciencedirect.com/science/article/pii/S1462901117308092>
<https://doi.org/10.1016/j.envsci.2017.08.008>
- Wiese, A., Luke, R., Heyns, G.J. & Pisa, N.M. 2015. The integration of lean, green and best practice business principles. *Journal of Transport and Supply Chain Management*, 9(1):1-10.
- Wilson, J. 2014. Essentials of business research: A guide to doing your research project.
- Wulf, F., Hagedorn, L., Munier, L., Balder, J., Mathi, C., Stark, R. & Pfriem, A. 2024. Towards digitalization of the circular economy in the furniture industry. *Sustainable Production and Consumption*, 52:45-62. <https://www.sciencedirect.com/science/article/pii/S2352550924002963>
<https://doi.org/10.1016/j.spc.2024.10.010>
- Xiao, Y. & Watson, M. 2019. Guidance on conducting a systematic literature review. *Journal of planning education and research*, 39(1):93-112.
- Yeh, R.T. 2019. Towards a framework for transdisciplinary problem solving. *Transdisciplinary Journal of Engineering & Science*, 10,
- Yildiz, A. & Yayla, A.Y. 2015. Multi-criteria decision-making methods for supplier selection: A literature review. *South African Journal of Industrial Engineering*, 26(2):158-177.
- Zare, F., Jakeman, A.J., Elsayah, S. & Guillaume, J.H. 2024. Bridging practice and science in socio-environmental systems research and modelling: A design science approach. *Ecological Modelling*, 492:110719.
- Zeng, Y., Maxwell, S., Runting, R.K., Venter, O., Watson, J.E. & Carrasco, L.R. 2020. Environmental destruction not avoided with the Sustainable Development Goals. *Nature Sustainability*, 3(10):795-798.
- Zexian, Y. & Xuhui, Y. 2010. A revolution in the field of systems thinking—a review of Checkland's system thinking. *Systems Research and Behavioral Science: The Official Journal of the International Federation for Systems Research*, 27(2):140-155.
- Zhu, F. & Tsai, W.-T. 1998. Framework-oriented analysis. In. Proceedings. The Twenty-Second Annual International Computer Software and Applications Conference (Compsac'98)(Cat. No. 98CB 36241). IEEE. pp. 324-329.
- Zierhofer, W. & Burger, P. 2007. Disentangling transdisciplinarity: an analysis of knowledge integration in problem-oriented research. *Science & Technology Studies*, 20(1):51-72.

- Zokaei, K., Lovins, H., Wood, A. & Hines, P. 2013. *Creating a lean and green business system: techniques for improving profits and sustainability*. CRC press.
- Zokaei, K., Lovins, H., Wood, A. & Hines, P. 2017. *Creating a lean and green business system: techniques for improving profits and sustainability*. Productivity Press.

Appendix A

Proof of ethics training

This appendix contains proof of ethics training done online and issued by Macquarie University 21 June 2022.



Certificate

June 21, 2022

This is to certify that Mr. Meelan Roopa has successfully completed the Macquarie University Human Research Ethics Online Training Module for the Social Sciences and Humanities.

Macquarie University

Appendix B

Ethics approval letter of study

This appendix contains the ethics approval letter of study to conduct the interviews. This was provided 27 March 2024 with ethics number from ENG-REC being NWU-00235-23-A3. Kindly note that the title of the study had changed in 2025 to its current form.



Private Bag X1290, Potchefstroom
South Africa 2520

North-West University Engineering Research
Ethics Committee (NWU-ENG-REC)

Tel: 018 299-1575
Email: ENG-REC@nwu.ac.za

27 March 2024

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 1 November 2023, the NWU-ENG-REC hereby approves your last phase of your study as indicated below. This implies that the NWU-ENG-REC grants its permission that, provided the general and specific conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title: Harnessing Industrial Engineering Knowledge for Environmental Sustainability Adoption in South Africa			
Study leader: Prof Raj Siriram			
Student: Meelan Roopa			
Ethics number:	NWU-00235-23-A3		
	Institution	Study Number	Year Status
Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation			
Application Type: Single		Risk:	Low Risk
Approval date: 1 November 2023			
Expiry date: 1 November 2024			
Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of annual monitoring report and the concomitant issuing of a letter of continuation.			

General conditions: While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply: - The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-ENG-REC: - Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and - without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study. - The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-ENG-REC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited. - Annually a number of studies may be randomly selected for active monitoring. - The date of approval indicates the first date that the study may be started. - In the interest of ethical responsibility, the NWU-ENG-REC reserves the right to:

- request access to any information or data at any time during the course or after completion of the study;
- to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;
- withdraw or postpone approval if:
 - any unethical principles or practices of the study are revealed or suspected;
 - it becomes apparent that any relevant information was withheld from the NWU-ENG-REC or that information has been false or misrepresented;
 - submission of the annual monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or
 - new institutional rules, national legislation or international conventions deem it necessary.
- NWU-ENG-REC can be contacted for further information via ENG-REC@nwu.ac.za or 018 299 2645

Special conditions of the research approval (if applicable): NA

Special in process conditions of the research for approval (if applicable): NA

The NWU-ENG-REC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,



Prof. P. Van Vuuren
Chair NWU-ENG-REC

Current details:(25767984) \NWU\NextCloud\ENG-REC\Letters sent\{Date}\9.1.5.4.3_NWU-ENG-REC_REC_EAL_{student surname_name}

File Reference: 9.1.5.4.2

Appendix C

Consolidated knowledge components

This appendix provides an outline of the various knowledge components pertaining to the study used to craft the TD artefact prior to PWTA.

Table 16: Integrated knowledge components used for PWTA

Knowledge component	Element	Citation count/Participant count
IE Strategy	Resource consumption	1
ES Strategy	Reducing carbon footprint, emissions and energy	4
ES Strategy	Reduce water consumption	1
ES Strategy	Reduce energy consumption	2
ES Theory	LCA	5
IE & ES method and practice	Fishbone diagram	1
IE method and practice	Efficiency	2
ES method and practice	Sustainability assessment	2
ES Strategy	Eutrophication	1
IE Strategy	Industry 4.0	2
IE Strategy	Leapfrogging	1
IE Strategy	Technology innovation	4
ES Strategy	Low carbon impact, dematerialization, decarbonization and substitution	1
ES Theory	Green manufacturing	1
ES Theory	DFE principles	1
IE method and practice	Sustainable manufacturing	2
IE Strategy	Product design	1
ES Strategy	Green product and environmental innovation	1
ES Strategy	Sustainable product development	1
ES Strategy	Global and engineered systems	1
ES Theory	Cradle to Cradle	1
ES Theory	System and planetary boundaries	2
IE Strategy	DSS and data analytics	2

Knowledge component	Element	Citation count/Participant count
IE Theory	Analytical models, algorithms and machine learning	8
IE Theory	Multicriteria decision analysis	1
IE Theory	Simulations	3
ES Theory	BIM	1
IE method and practice	Quantitative methods	3
IE Strategy	Business strategy and profitability	3
IE Theory	Games Theory	1
ES Theory	Games Theory	1
ES Strategy	The resource-based view	3
ES Strategy	Energy labelling	1
IE Theory	Facility planning	1
ES method and practice	Emergy	2
IE Strategy	Risk mitigation	1
ES Strategy	Risk management	1
IE Theory	Risk management	1
IE & ES method and practice	Auditing	3
ES Strategy	LEED	2
ES Strategy	Sustainable lifestyles	1
ES Theory	Agency Theory	1
ES Theory	Greenwashing	1
ES Theory	Institutional and distributive justice theory	2
ES Theory	Moore's Law	1
ES Theory	Product and human ecology	2
ES Theory	LEADS	1
ES Theory	STRETCH	1

Knowledge component	Element	Citation count/Participant count
IE method and practice	Training and incentivisation	1
ES Strategy	Resource strategy & 3R	3
ES Strategy	Clean production	1
IE Theory	Lean	5
ES Theory	Cleaner and safer production	1
IE Strategy	Supply chain management	1
ES Strategy	Supplier evaluation	1
ES Strategy	Supply chain	3
IE Theory	Supply chain sustainability, reversed logistics and closed loop supply chains	5
IE & ES method and practice	Green supply chain	2
ES Strategy	Triple bottom-line	1
ES Strategy	Sustainable resource management and life cycle thinking	1
ES Theory	EMS	1
ES Strategy	Circular economy and sharing principles	5
ES Strategy	Scientific knowledge creation	1
ES Strategy	Environmental protection and management	3
ES Strategy	Planetary Boundary	1
ES Strategy	Eco-effective symbiosis and industrial park	2
IE Theory	Value engineering and creation	3
IE Theory	Green engineering	1
ES Theory	Sustainable development and sustainability models	2
ES Theory	Ecological engineering and modernization theory	2

Knowledge component	Element	Citation count/Participant count
ES Theory	Environmental reform	1
ES Theory	Industrial ecosystems and eco-industrial systems	3
ES Theory	Circular humansphere	1
ES Theory	Industrial ecology	1
IE-ES Strategy	Sustainable Development Goals	9
IE-ES Strategy	Circular economy	8
IE-ES Strategy	Systems thinking	5
IE-ES Strategy	Efficiency (resources and operations)	5
IE-ES Strategy	Culture integration	4
IE-ES Strategy	Socio-technical transitions	4
IE-ES Strategy	Technology & Innovation	3
IE-ES Strategy	Continuous improvement	3
IE-ES Strategy	Minimising waste stream	3
IE-ES Strategy	Business models for sustainability	3
IE-ES Strategy	Triple bottom line	2
IE-ES Strategy	Carbon neutrality	2
IE-ES Strategy	People, Planet and Profits	2
IE-ES Strategy	Cross disciplinary	2
IE-ES Strategy	Data driven decision making	2
IE-ES Strategy	Monetization	2
IE-ES Strategy	Shared value	2
IE-ES Strategy	Corporate social responsibility	2
IE-ES Strategy	Decarbonization roadmap	1
IE-ES Strategy	Material substitution	1
IE-ES Strategy	EFQM model	1
IE-ES Strategy	Resource-based perspective	1
IE-ES Strategy	High quality	1

Knowledge component	Element	Citation count	count/Participant
IE-ES Strategy	Corporate sustainability	1	
IE-ES Strategy	Reduce emissions	1	
IE-ES Strategy	Radical redesign	1	
IE-ES Strategy	Maturity models	1	
IE-ES Strategy	Reduce carbon footprint	1	
IE-ES Strategy	Life cycle view	1	
IE-ES Theory	Lean	11	
IE-ES Theory	Project Management	8	
IE-ES Theory	Simulation	7	
IE-ES Theory	Life cycle assessment & analysis	7	
IE-ES Theory	Six Sigma	6	
IE-ES Theory	Optimisation	5	
IE-ES Theory	Supply chain management	5	
IE-ES Theory	Biomimicry	5	
IE-ES Theory	Systems thinking	4	
IE-ES Theory	Theory of constraints	4	
IE-ES Theory	Problem solving methods	3	
IE-ES Theory	Value chain optimisation	3	
IE-ES Theory	Multi-level perspectives	3	
IE-ES Theory	Quality management	3	
IE-ES Theory	Systems engineering	3	
IE-ES Theory	Mathematics & Statistics	3	
IE-ES Theory	Management theory	2	
IE-ES Theory	Motivational theories	2	
IE-ES Theory	Financial management	2	
IE-ES Theory	Decarbonization	2	
IE-ES Theory	Systems dynamics	2	
IE-ES Theory	Operational excellence	2	

Knowledge component	Element	Citation count	count/Participant
IE-ES Theory	Cradle to grave	2	
IE-ES Theory	Artificial Intelligence	2	
IE-ES Theory	Operations management	2	
IE-ES Theory	Leadership	2	
IE-ES Theory	Product life cycle management	2	
IE-ES Theory	Change management	2	
IE-ES Theory	Design thinking	2	
IE-ES Theory	Sustainable value chains	2	
IE-ES Theory	Facilities design	2	
IE-ES Theory	Scenario planning & analysis	2	
IE-ES Theory	Carbon footprinting	1	
IE-ES Theory	Soft systems methodology	1	
IE-ES Theory	Machine learning	1	
IE-ES Theory	Sustainability resilience	1	
IE-ES Theory	Renewable energy development	1	
IE-ES Theory	Value engineering	1	
IE-ES Theory	Operations research	1	
IE-ES Theory	Managerial discretion	1	
IE-ES Theory	Boundary expansion	1	
IE-ES Theory	Green growth	1	
IE-ES Theory	Soft systems thinking	1	
IE-ES Theory	Industrial ecology	1	
IE-ES Theory	CYNEFIN model	1	
IE-ES Theory	Future thinking	1	
IE-ES Theory	Design For Environment	1	
IE-ES Theory	Risk management	1	
IE-ES Theory	Energy management	1	
IE-ES Theory	Industrial symbiosis	1	

Knowledge component	Element	Citation count	count/Participant
IE-ES Theory	Transition literature	1	
IE-ES Method or practice	ESG reporting	8	
IE-ES Method or practice	Data analysis	5	
IE-ES Method or practice	Recycling	4	
IE-ES Method or practice	3R, 6R, 12R	4	
IE-ES Method or practice	Value stream mapping	4	
IE-ES Method or practice	Linear programming	3	
IE-ES Method or practice	5S	3	
IE-ES Method or practice	Polluter pays principle	3	
IE-ES Method or practice	Carbon trading	3	
IE-ES Method or practice	Feasibility study	3	
IE-ES Method or practice	Benchmarking	3	
IE-ES Method or practice	Root cause analysis	3	
IE-ES Method or practice	Fishbone	3	
IE-ES Method or practice	Business strategic tools	3	
IE-ES Method or practice	Environmental audits	2	
IE-ES Method or practice	Carbon tax	2	
IE-ES Method or practice	Carbon capture	2	
IE-ES Method or practice	Legislation and policy	2	
IE-ES Method or practice	Material flow analysis	2	
IE-ES Method or practice	Standard operating procedures	2	
IE-ES Method or practice	Product design and regeneration	2	
IE-ES Method or practice	Supply chain optimisation	2	
IE-ES Method or practice	Greenwashing	2	
IE-ES Method or practice	PROCI	2	
IE-ES Method or practice	Water and energy consumption	2	
IE-ES Method or practice	Workforce upskilling	2	
IE-ES Method or practice	PDCA	2	

Knowledge component	Element	Citation count	Participant count
IE-ES Method or practice	Current state analysis	2	
IE-ES Method or practice	Greenhouse gas protocols	1	
IE-ES Method or practice	Forecasting	1	
IE-ES Method or practice	Regression analysis	1	
IE-ES Method or practice	Software	1	
IE-ES Method or practice	Upcycling	1	
IE-ES Method or practice	Business process mapping	1	
IE-ES Method or practice	Scope emissions	1	
IE-ES Method or practice	KPI tree	1	
IE-ES Method or practice	Stakeholder analysis	1	
IE-ES Method or practice	Environmental monitoring	1	
IE-ES Method or practice	Standardization	1	
IE-ES Method or practice	Eco machines	1	
IE-ES Method or practice	SWOT analysis	1	
IE-ES Method or practice	SCRUM	1	
IE-ES Method or practice	Communication	1	
IE-ES Method or practice	11 GA outcomes for ECSA	1	
IE-ES Method or practice	Sound judgement	1	
IE-ES Method or practice	Waste reduction	1	
IE-ES Method or practice	Facility & process design	1	
IE-ES Method or practice	Work study	1	
IE-ES Method or practice	Net zero waste	1	
IE-ES Method or practice	Data visualization	1	
IE-ES Method or practice	Value chain optimisation	1	
IE-ES Method or practice	Sensitivity analysis	1	
IE-ES Method or practice	5 Whys	1	
IE-ES Method or practice	Reverse logistics	1	
IE-ES Method or practice	FMEA	1	

Knowledge component	Element	Citation count	count/Participant
IE-ES Method or practice	SIPOC diagrams	1	
IE-ES Method or practice	Load curtailment	1	
IE-ES Method or practice	New technology	1	
IE-ES Method or practice	Batch processing	1	
IE-ES Method or practice	Statistical analysis	1	
IE-ES Method or practice	Circular supply chain	1	
IE-ES Method or practice	Pareto Analysis	1	
IE-ES Method or practice	Critical thinking	1	
IE-ES Method or practice	DMAIC	1	
IE-ES Method or practice	Business process re-engineering	1	
IE-ES Method or practice	Ethical decision making	1	
IE-ES Method or practice	Intelligent manufacturing	1	

Appendix D

Pareto analysis of all knowledge components

This appendix provides the 80/20 threshold points used on the coded densities for the integrated knowledge components used to create the TD artefact.

Table 17 Integrated knowledge component PWTa calculations

Knowledge component	Element	Citation count	Proportion	Cumulated
IE-ES Theory	Lean and Green	16	3.49%	3.49%
IE-ES Strategy	Circular economy	15	3.27%	6.75%
IE-ES Theory	Simulation	10	2.18%	8.93%
IE Theory	Analytical models, algorithms and machine learning	9	1.96%	10.89%
IE-ES Theory	Supply chain management	9	1.96%	12.85%
IE-ES Strategy	Sustainable Development Goals	9	1.96%	14.81%
IE-ES Method or practice	ESG reporting	8	1.74%	16.56%
IE-ES Theory	Project Management	8	1.74%	18.30%
IE-ES Strategy	Efficiency	7	1.53%	19.83%
IE-ES Theory	Life cycle assessment & analysis	7	1.53%	21.35%
IE-ES Strategy	Systems thinking	7	1.53%	22.88%
IE-ES Strategy	Technology & Innovation	7	1.53%	24.40%
IE-ES Theory	Six Sigma	6	1.31%	25.71%
IE-ES Theory	Biomimicry	5	1.09%	26.80%
IE-ES Method or practice	Data analysis	5	1.09%	27.89%
IE-ES Strategy	Environmental management	5	1.09%	28.98%
ES Theory	LCA	5	1.09%	30.07%
IE-ES Theory	Optimisation	5	1.09%	31.15%
IE Theory	Supply chain sustainability, reversed logistics and closed loop supply chains	5	1.09%	32.24%
IE-ES Method or practice	3R, 6R, 12R	4	0.87%	33.12%
IE-ES Strategy	Culture integration	4	0.87%	33.99%
IE-ES Theory	Facilities design	4	0.87%	34.86%
IE-ES Method or practice	Fishbone diagram	4	0.87%	35.73%
IE-ES Method or practice	Recycling	4	0.87%	36.60%

Knowledge component	Element	Citation count	Proportion	Cumulated
ES Strategy	Reducing carbon footprint, emissions and emergy	4	0.87%	37.47%
IE-ES Strategy	Socio-technical transitions	4	0.87%	38.34%
IE-ES Theory	Theory of constraints	4	0.87%	39.22%
IE-ES Theory	Value engineering	4	0.87%	40.09%
IE-ES Method or practice	Value stream mapping	4	0.87%	40.96%
IE-ES Method or practice	5S	3	0.65%	41.61%
IE & ES method and practice	Auditing	3	0.65%	42.27%
IE-ES Method or practice	Benchmarking	3	0.65%	42.92%
IE-ES Strategy	Business models for sustainability	3	0.65%	43.57%
IE-ES Method or practice	Business strategic tools	3	0.65%	44.23%
IE Strategy	Business strategy and profitability	3	0.65%	44.88%
IE-ES Method or practice	Carbon trading	3	0.65%	45.53%
IE-ES Strategy	Continuous improvement	3	0.65%	46.19%
IE-ES Strategy	Corporate social responsibility	3	0.65%	46.84%
ES Theory	Cradle to Cradle	3	0.65%	47.49%
IE-ES Method or practice	Feasibility study	3	0.65%	48.15%
IE-ES Method or practice	Prevent Greenwashing	3	0.65%	48.80%
ES Theory	Industrial ecosystems and eco-industrial systems	3	0.65%	49.46%
IE-ES Method or practice	Linear programming	3	0.65%	50.11%
IE-ES Theory	Mathematics & Statistics	3	0.65%	50.76%
IE-ES Strategy	Minimising waste stream	3	0.65%	51.42%
IE-ES Theory	Multi-level perspectives	3	0.65%	52.07%
IE-ES Method or practice	Polluter pays principle	3	0.65%	52.72%
IE-ES Theory	Problem solving methods	3	0.65%	53.38%
IE-ES Strategy	Product design and regeneration	3	0.65%	54.03%

Knowledge component	Element	Citation count	Proportion	Cumulated
IE-ES Theory	Quality management	3	0.65%	54.68%
IE method and practice	Quantitative methods	3	0.65%	55.34%
ES Strategy	Resource strategy & 3R	3	0.65%	55.99%
IE-ES Theory	Risk management	3	0.65%	56.64%
IE-ES Method or practice	Root cause analysis	3	0.65%	57.30%
IE-ES Theory	Systems engineering	3	0.65%	57.95%
ES Strategy	The resource-based view	3	0.65%	58.61%
IE-ES Strategy	Triple bottom line	3	0.65%	59.26%
IE-ES Theory	Artificial Intelligence	2	0.44%	59.69%
IE-ES Method or practice	Carbon capture	2	0.44%	60.13%
IE-ES Strategy	Carbon neutrality	2	0.44%	60.57%
IE-ES Method or practice	Carbon tax	2	0.44%	61.00%
IE-ES Theory	Change management	2	0.44%	61.44%
IE-ES Strategy	Cross disciplinary	2	0.44%	61.87%
IE-ES Method or practice	Current state analysis	2	0.44%	62.31%
IE-ES Strategy	Data driven decision making	2	0.44%	62.75%
IE-ES Theory	Decarbonization	2	0.44%	63.18%
IE-ES Theory	Design For Environment (DFE)	2	0.44%	63.62%
IE-ES Theory	Design thinking	2	0.44%	64.05%
IE Strategy	DSS and data analytics	2	0.44%	64.49%
ES Strategy	Eco-effective symbiosis and industrial park	2	0.44%	64.92%
ES Theory	Ecological engineering and modernization theory	2	0.44%	65.36%
ES method and practice	Emergy	2	0.44%	65.80%
IE-ES Method or practice	Environmental audits	2	0.44%	66.23%
IE-ES Theory	Financial management	2	0.44%	66.67%
IE-ES Theory	Games Theory	2	0.44%	67.10%

Knowledge component	Element	Citation count	Proportion	Cumulated
IE & ES method and practice	Green supply chain	2	0.44%	67.54%
IE-ES Theory	Industrial ecology	2	0.44%	67.97%
IE Strategy	Industry 4.0	2	0.44%	68.41%
ES Theory	Institutional and distributive justice theory	2	0.44%	68.85%
IE-ES Theory	Leadership	2	0.44%	69.28%
ES Strategy	LEED	2	0.44%	69.72%
IE-ES Method or practice	Legislation and policy	2	0.44%	70.15%
IE-ES Theory	Management theory	2	0.44%	70.59%
IE-ES Method or practice	Material flow analysis	2	0.44%	71.02%
IE-ES Strategy	Monetization	2	0.44%	71.46%
IE-ES Theory	Motivational theories	2	0.44%	71.90%
IE-ES Theory	Operational excellence	2	0.44%	72.33%
IE-ES Theory	Operations management	2	0.44%	72.77%
IE-ES Method or practice	PDCA	2	0.44%	73.20%
IE-ES Strategy	People, Planet and Profits	2	0.44%	73.64%
IE-ES Method or practice	PROCI	2	0.44%	74.07%
ES Theory	Product and human ecology	2	0.44%	74.51%
IE-ES Theory	Product life cycle management	2	0.44%	74.95%
ES Strategy	Reduce energy consumption	2	0.44%	75.38%
IE-ES Theory	Scenario planning & analysis	2	0.44%	75.82%
IE-ES Strategy	Shared value	2	0.44%	76.25%
IE-ES Method or practice	Standard operating procedures	2	0.44%	76.69%
IE-ES Method or practice	Supply chain optimisation	2	0.44%	77.12%
ES method and practice	Sustainability assessment	2	0.44%	77.56%
ES Theory	Sustainable development and sustainability models	2	0.44%	78.00%
IE method and practice	Sustainable manufacturing	2	0.44%	78.43%

Knowledge component	Element	Citation count	Proportion	Cumulated
IE-ES Theory	Sustainable value chains	2	0.44%	78.87%
ES Theory	System and planetary boundaries	2	0.44%	79.30%
IE-ES Theory	Systems dynamics	2	0.44%	79.74%
IE-ES Method or practice	Water and energy consumption	2	0.44%	80.17%
IE-ES Method or practice	Workforce upskilling	2	0.44%	80.61%
IE-ES Method or practice	11 GA outcomes for ECSA	1	0.22%	80.83%
IE-ES Method or practice	5 Whys	1	0.22%	81.05%
ES Theory	Agency Theory	1	0.22%	81.26%
IE-ES Method or practice	Batch processing	1	0.22%	81.48%
ES Theory	BIM	1	0.22%	81.70%
IE-ES Theory	Boundary expansion	1	0.22%	81.92%
IE-ES Method or practice	Business process mapping	1	0.22%	82.14%
IE-ES Method or practice	Business process re-engineering	1	0.22%	82.35%
IE-ES Theory	Carbon footprinting	1	0.22%	82.57%
ES Theory	Circular humansphere	1	0.22%	82.79%
IE-ES Method or practice	Circular supply chain	1	0.22%	83.01%
ES Strategy	Clean production	1	0.22%	83.22%
ES Theory	Cleaner and safer production	1	0.22%	83.44%
IE-ES Method or practice	Communication	1	0.22%	83.66%
IE-ES Method or practice	Critical thinking	1	0.22%	83.88%
IE-ES Theory	CYNEFIN model	1	0.22%	84.10%
IE-ES Method or practice	Data visualization	1	0.22%	84.31%
IE-ES Strategy	Decarbonization roadmap	1	0.22%	84.53%
IE-ES Method or practice	DMAIC	1	0.22%	84.75%
IE-ES Method or practice	Eco machines	1	0.22%	84.97%
IE-ES Strategy	EFQM model	1	0.22%	85.19%

Knowledge component	Element	Citation count	Proportion	Cumulated
ES Strategy	Energy labelling	1	0.22%	85.40%
IE-ES Theory	Energy management	1	0.22%	85.62%
ES Theory	Environmental reform	1	0.22%	85.84%
IE-ES Method or practice	Ethical decision making	1	0.22%	86.06%
ES Strategy	Eutrophication	1	0.22%	86.27%
IE-ES Method or practice	FMEA	1	0.22%	86.49%
IE-ES Method or practice	Forecasting	1	0.22%	86.71%
IE-ES Theory	Future thinking	1	0.22%	86.93%
ES Strategy	Global and engineered systems	1	0.22%	87.15%
IE Theory	Green engineering	1	0.22%	87.36%
IE-ES Theory	Green growth	1	0.22%	87.58%
ES Theory	Green manufacturing	1	0.22%	87.80%
ES Strategy	Green product and environmental innovation	1	0.22%	88.02%
IE-ES Method or practice	Greenhouse gas protocols	1	0.22%	88.24%
IE-ES Strategy	High quality	1	0.22%	88.45%
IE-ES Theory	Industrial symbiosis	1	0.22%	88.67%
IE-ES Method or practice	Intelligent manufacturing	1	0.22%	88.89%
IE-ES Method or practice	KPI tree	1	0.22%	89.11%
ES Theory	LEADS	1	0.22%	89.32%
IE Strategy	Leapfrogging	1	0.22%	89.54%
IE-ES Strategy	Life cycle view	1	0.22%	89.76%
IE-ES Method or practice	Load curtailment	1	0.22%	89.98%
ES Strategy	Low carbon impact, dematerialization, decarbonization and substitution	1	0.22%	90.20%
IE-ES Theory	Managerial discretion	1	0.22%	90.41%
IE-ES Strategy	Material substitution	1	0.22%	90.63%

Knowledge component	Element	Citation count	Proportion	Cumulated
IE-ES Strategy	Maturity models	1	0.22%	90.85%
ES Theory	Moore's Law	1	0.22%	91.07%
IE Theory	Multicriteria decision analysis	1	0.22%	91.29%
IE-ES Method or practice	Net zero waste	1	0.22%	91.50%
IE-ES Method or practice	New technology	1	0.22%	91.72%
IE-ES Theory	Operations research	1	0.22%	91.94%
IE-ES Method or practice	Pareto Analysis	1	0.22%	92.16%
ES Strategy	Planetary Boundary	1	0.22%	92.37%
IE-ES Strategy	Radical redesign	1	0.22%	92.59%
IE-ES Strategy	Reduce carbon footprint	1	0.22%	92.81%
IE-ES Strategy	Reduce emissions	1	0.22%	93.03%
ES Strategy	Reduce water consumption	1	0.22%	93.25%
IE-ES Method or practice	Regression analysis	1	0.22%	93.46%
IE-ES Theory	Renewable energy development	1	0.22%	93.68%
IE Strategy	Resource consumption	1	0.22%	93.90%
IE-ES Strategy	Resource-based perspective	1	0.22%	94.12%
IE-ES Method or practice	Reverse logistics	1	0.22%	94.34%
IE Strategy	Risk mitigation	1	0.22%	94.55%
ES Strategy	Scientific knowledge creation	1	0.22%	94.77%
IE-ES Method or practice	Scope emissions	1	0.22%	94.99%
IE-ES Method or practice	SCRUM	1	0.22%	95.21%
IE-ES Method or practice	Sensitivity analysis	1	0.22%	95.42%
IE-ES Method or practice	SIPOC diagrams	1	0.22%	95.64%
IE-ES Theory	Soft systems methodology	1	0.22%	95.86%
IE-ES Theory	Soft systems thinking	1	0.22%	96.08%
IE-ES Method or practice	Software	1	0.22%	96.30%
IE-ES Method or practice	Sound judgement	1	0.22%	96.51%

Knowledge component	Element	Citation count	Proportion	Cumulated
IE-ES Method or practice	Stakeholder analysis	1	0.22%	96.73%
IE-ES Method or practice	Standardization	1	0.22%	96.95%
IE-ES Method or practice	Statistical analysis	1	0.22%	97.17%
ES Theory	STRETCH	1	0.22%	97.39%
IE-ES Method or practice	Supplier evaluation	1	0.22%	97.60%
IE-ES Theory	Sustainability resilience	1	0.22%	97.82%
ES Strategy	Sustainable lifestyles	1	0.22%	98.04%
ES Strategy	Sustainable product development	1	0.22%	98.26%
ES Strategy	Sustainable resource management	1	0.22%	98.47%
IE-ES Method or practice	SWOT analysis	1	0.22%	98.69%
IE method and practice	Training and incentivisation	1	0.22%	98.91%
IE-ES Theory	Transition literature	1	0.22%	99.13%
IE-ES Method or practice	Upcycling	1	0.22%	99.35%
IE-ES Method or practice	Value chain optimisation	1	0.22%	99.56%
IE-ES Method or practice	Waste reduction	1	0.22%	99.78%
IE-ES Method or practice	Work study	1	0.22%	100.00%

Appendix E

Confirmation letter for accepted conference paper

This appendix provides a confirmation letter for paper 326 being accepted and presented at the International Conference on Engineering, Technology and Innovation June 2026.

2026 IEEE 32nd International Conference on Engineering, Technology, and
Innovation (ICE 2026)
Meelan Roopa
Stellenbosch University | North-West University
South Africa

UNINOVA
Campus NOVA FCT
2829-516 Caparica
Portugal

Acceptance Letter

To Whom it May Concern

We are pleased to inform that the following author has been officially accepted to participate and present a paper at the **32nd International Conference on Engineering, Technology, and Innovation (ICE 2026)**, which will take place on **22-24 June 2026** in **Porto, Portugal**.

Author Information

- Full Name: Meelan Roopa
- Institution: Stellenbosch University | North-West University
- Date of Birth: 04/03/1996
- Passport Number: UA20718140

Accepted Paper(s) Information

- Paper Title: *"A Lean and Green Hoshin Kanri framework for an automobile aftersales service centre"*
- Paper ID/Number: ID172
- Conference Track/Session (optional): General Track – ENGINEERING
- Paper Title: *"A simulation study on the workflow of a South African automotive aftersales service facility"*
- Paper ID/Number: ID323
- Conference Track/Session (optional): General Track – ENGINEERING
- Paper Title: *"A multi-use case analysis for a sustainable competitive advantage using industrial engineering and environmental sustainability knowledge"*
- Paper ID/Number: ID326
- Conference Track/Session (optional): General Track – ENGINEERING

The submitted paper has successfully passed the review process and has been accepted for presentation and inclusion in the conference proceedings.

Please note that the participation and presentation of the paper at ICE 2026 will only be considered valid after the completion of the conference registration process and payment of the corresponding registration fee.

Furthermore, the organizers of ICE 2026 (UNINOVA, IDEA, UMinho, NOVA School of Science and Technology, NOVA University Lisbon, IEEE/TEMS and IEEE) are not responsible for the registration, travel, accommodation, or living expenses of the participant.

This letter is issued upon request for official and administrative purposes, including visa application and travel arrangements.

Should you require any further information, please feel free to contact us.

Caparica, 08th May 2026

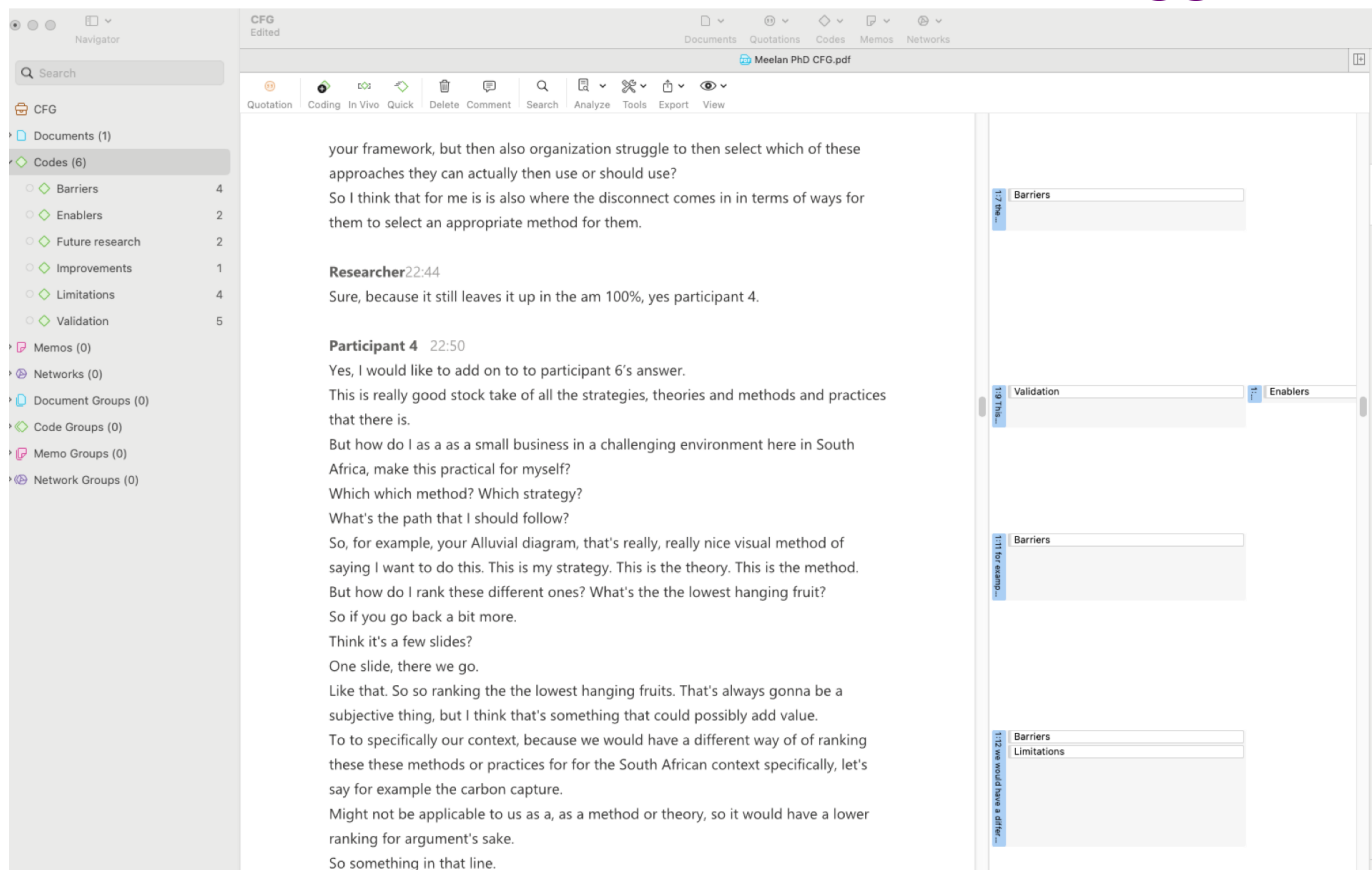
A handwritten signature in black ink, appearing to be "R. Jardim", written over a horizontal line.

Ricardo Luís Rosa Jardim Gonçalves
ICE 2024 General Chair

Appendix F

Confirmatory Focus Group sample of transcript analysed

This appendix provides a sample of the Confirmatory Focus Group transcript which was coded in atlas.ti



your framework, but then also organization struggle to then select which of these approaches they can actually then use or should use?

So I think that for me is also where the disconnect comes in in terms of ways for them to select an appropriate method for them.

Researcher 22:44
Sure, because it still leaves it up in the am 100%, yes participant 4.

Participant 4 22:50
Yes, I would like to add on to to participant 6's answer.
This is really good stock take of all the strategies, theories and methods and practices that there is.
But how do I as a small business in a challenging environment here in South Africa, make this practical for myself?
Which which method? Which strategy?
What's the path that I should follow?
So, for example, your Alluvial diagram, that's really, really nice visual method of saying I want to do this. This is my strategy. This is the theory. This is the method. But how do I rank these different ones? What's the the lowest hanging fruit?
So if you go back a bit more.
Think it's a few slides?
One slide, there we go.
Like that. So so ranking the the lowest hanging fruits. That's always gonna be a subjective thing, but I think that's something that could possibly add value.
To to specifically our context, because we would have a different way of of ranking these these methods or practices for for the South African context specifically, let's say for example the carbon capture.
Might not be applicable to us as a, as a method or theory, so it would have a lower ranking for argument's sake.
So something in that line.

Barriers

Validation

Enablers

Barriers

Barriers

Limitations